POTENTIAL FOR PROCESS IMPROVEMENT OF THE RUBBER GLOVE MANUFACTURING PROCESS - AN INDUSTRIAL CASE STUDY

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ABSTRACT

Coagulant dipping constitutes an important part of the rubber glove manufacturing process. Its operation is affected by many variables which dictates the quality of the finished product. Therefore, investigating the controllable factors affecting the quality of the product and process in the presence of noise factors for process improvement is the primary aim of this study.

Robust process design for off-line quality control has received much attention in the literature. Application of this design in the rubber examination glove industry as an alternative solution for potential competitive advantage was investigated. The robust design problem is defined in terms of design objectives, controllable factors and noise factors. In this thesis we combined both controllable and noise factors as a single experimental set-up. An L16 orthogonal array was used as it would allow the evaluation of the eight main factors chosen and some of their interactions. The use of fractional factorial reduces the number of runs required.

Physical experiments were conducted in the glove manufacturing plant for the case problem. Effects of experimental errors, model assumptions, the experimental design and modelling approaches on the results are discussed. Models capable of predicting the response performance of the process under study are developed and investigated. Experience learnt from the implementation of quality improvement which are human related factors are also addressed in this thesis.

From this study we gained a better understanding of the rubber glove manufacturing process. We are therefore in a better position to see what levels of the independent factors will lead to acceptable response values and acceptable variability. This approach allows us to make appropriate compromises between a target value for the response of interest and resulting variance. The additional knowledge were not known before. It could be used as an advantage for the glove manufacturers to better control their processes. The enormous potential benefits that could be reaped from the information gained about the process quantify the efforts for improvements.

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CHAPTER 1

INTRODUCTION

1.1 Overview of Rubber-Based Industry in Malaysia

Rubber products manufacturing in Malaysia started in the late 1910s but remained insignificant despite Malaysia being the world's biggest supplier of natural rubber. The industry began to expand only after the 1970s. This development has been partly due to the recommendation in 1972 by the Rubber Research Institute of Malaysia to identify growth areas in the quest for natural rubber based industrialisation. Therefore, the nature of agriculture changed drastically in favour of higher value added activities. Naturally this structural change has had an impact on the rubber industry. Natural rubber has progressively evolved from being an agricultural product to an input for manufacturing processes. Malaysia is now metamorphosing rapidly from an agriculture based country to an industrialised economy. Thus, while the major contribution to the national economy had come from agriculture in the 1960s and 1970s, the manufacturing sector had become dominant since the 1980s. The boom in the manufacturing sector was catalysed by the implementation of the Industrial Master Plan (IMP). The government has provided a wide range of manufacturing export incentives to facilitate the industrialisation process. Within the context of rubber based products, a number of multi-national companies have begun to set up production facilities in Malaysia, which greatly diversified the range of latex products to include items such as gloves, condoms, catheters and teats. Foreign investment has brought with it world-class technologies, as well as management and marketing skills which are transferred from the parent companies.

In contrast to this, most of the local Malaysian companies fall under the small and medium scale manufacturing category, in terms of paid up capital and production capacity. The technological capability of small and medium scale industries varies. Generally, however, most of the locally owned companies possess medium, or somewhat above average level of technological competence.

The statistics released by the Malaysian Department of Statistics and Malaysian Industrial Development Authority (MIDA) 1994; showed that since early 1988, there has been an increase in the number of examination glove manufacturers in Malaysia. This has been the result of the global concern about diseases such as AIDS, HIV and hepatitis and so the demand and price for latex gloves, especially in the US, have risen. It is also partly due to the current trend of open economies which offer increased opportunities for the growth of the glove industry all over the world. Consequently, glove manufacturing plants have begun to mushroom all over the country in a frantic attempt to capitalise on the booming glove market. More than 400 glove manufacturing proposals were approved by MIDA during the 1988-1989 period but fewer than half came into production. By the end of 1989, the industry comprised of 237 manufacturers, of which, some 130 were glove manufacturers.

1.2 Challenges Facing the Industry and Its Future Development

Today, the manufacture of natural rubber examination gloves has become competitive and is expected to become even more competitive in the near future. This industry has a dual structure characterised by differences in business size, type of ownership, level of technology and market outlet. Foreign-owned or joint-venture companies which are usually bigger than the locally-owned operations, possess relatively higher levels of technological competence. Therefore they are capable of adjusting readily to market changes by modifying the product and process lines. On the other hand, the locally-owned companies are relatively new players, and those that could not absorb the initial losses have been forced out of the industry.

This situation was very obvious when the world glove market collapsed in 1989 due to over supply and, as a result, about 40 glove manufacturers, mostly the new and inexperienced, closed down. By the end of 1991, the size of the industry had shrunk to 206 with glove manufacturers numbering around 80. As the glove market began to consolidate and recover in the early 1990s, many manufacturers re-started production, thereby expanding the size of the industry to 264 in 1993. By early 1995, the Malaysian rubber glove industry seemed to be approaching a cross-road. While demand for latex gloves has remained strong manufacturers, nevertheless, felt concerned over the current issues that had cropped up. These were :

(1) The rapidly rising cost in production without a concomitant increase in glove prices.

(2) Substantial increases in latex price by some 40% eroded profit margins resulting in some manufacturers incurring losses to fixed gloves' prices contracted earlier. According to a survey, MARGMA (Malaysian Rubber Glove Manufacturers' Association) 1995, latex constituted about 50 % of the average total production costs.

(3) There were also increases in the costs of packaging material and labour.

(4) Aside from this, the Malaysian industry is faced with problems of acute labour shortage. The employment of foreign workers appeared to provide temporary relief for some but at a high cost initially in order to bring them in.

(5) Natural rubber examination gloves have been manufactured as an export commodity. The marketing of rubber gloves has been highly competitive. While neighbouring countries such as Thailand and Indonesia still have a cheap and abundant labour force.

It has been a known fact that the rubber gloves industry is labour intensive. However, this was ignored in the late eighties and early nineties when investors jumped onto the bandwagon, grabbing the incentives that came their way in the form of pioneer status; 20% rebate on power; 20 cents per kilogram rebate on rubber, etc. Now, all these incentives are gradually being removed. To top it all, many locally-owned Malaysian glove companies are not sufficiently well-versed in the many quality aspects governing glove manufacture. Consequently quality activities are generally carried out as quality inspections. Further discussion of quality problems faced by the rubber glove manufacturers will be presented in section 2.9 of chapter 2.

There is therefore a clear need for efficient and effective strategies to respond to these challenges facing the industry and its future, as poor quality cannot be improved by the process of inspection, screening and salvaging. No amount of inspection can put quality back into the product. Therefore, quality improvement should be based upon and developed around the philosophy of prevention. According to Deming (1986) 85% of poor quality is attributed to the manufacturing process and only 15% to workers.

Hence, the better way to improve quality is to design and build it into the product. Statistical methods provide the means for understanding the operating characteristics of a process and the causes of in-process variation. In this connection, our approach is to develop an "off-line" strategy for quality improvement. Another possibility is to look at an on-line quality improvement. At an initial stage of the approach, on-line quality improvement will be adopted in order to investigate the source of variation. The only limitation of this approach is that it is unable to tell which operating factor levels contribute to output variations and how to improve them. Once quality has been designed into products and processes upstream, and important factors have been identified, an on-line method such as Statistical Process Control can be used to monitor and maintain that quality during production. The application of experimental design can serve as an important tool in process development and process trouble shooting to improve performance. This method is able to solve problems involving several variables and interactions. It is a systematic method of optimising a production process, and is concerned with quality, productivity enhancements and cost effectiveness of production. Application of this technique has not been used in the rubber glove industry especially in locally-owned Malaysian rubber gloves companies. Thus the future of this industry depends to a large extent on the potential benefits that this technique can offer. Fearn and Wynn (1996) pointed out that although experimenting complex processes is not easy, particularly in a full-scale production environment, the potential benefits are great enough to quantify the effort.

In this case study, we look at integrating statistical design of experiment and the concept of robustness as a way of improving both product quality and process efficiency and hence, yields more consistent and better quality gloves. We hope to learn more about the process which is currently not very well understood. Once we understand the process better, we might be in a position to identify what changes, if any, in raw material inputs, operating procedure and in hardware are needed to implement improvements. In short, if previously we had a limited understanding of the process, now, we will learn how to control the process, indeed, we may not have to control factors not affecting the process output.

In our approach to this present study, we will also focus on aspects of the human element, an essential ingredient for effective implementation of the quality improvement efforts. The appropriate technologies, tools and techniques can be acquired quite readily, as long as the management is willing to invest. However, the major concern and often a practical issue, are the implementation and sustaining phases of the programme. This needs to be addressed vigilantly in order to realise the valuable potential benefits.

Management has to establish a responsive environment which demands the revampment of "fire fighting" and "finger pointing" culture. All these could not be achieved overnight. Instead they have to be planned and put in place.

1.3 Objectives of the Study

The objectives of the present study are to :

(1) Gain a better understanding and additional knowledge about the rubber glove manufacturing process.

(2) Investigate and identify control factors that affect product quality.

(3) Establish controllable factor levels that will yield optimal output.

(4) Develop models which show combined effects of the controllable factors levels in the presence of noise factors.

(5) Reduce product variability and improve the robustness of the manufacturing process.

(6) Address the issue of human factors in the implementation of quality improvements.

With a better understanding of the production process, it is hoped that more appropriate strategies can be formulated for the whole rubber glove industry in order to enhance its competitive edge and longer term survival of the industry.

This case study was conducted in a medium sized company with a paid-up capital of $500,000 Malaysian Ringgit. It is locally-owned Malaysian rubber glove company.

1.4 Methodology

This study was conducted as follows:-

(1) Collect raw data from the existing process.

(2) Examine the data.

(3) Formulate the theory and strategy for improving the process. The theory is based on prevention principle. It is much more effective to avoid waste by not producing unusable output in the first place. By building in quality in the process and product, we could achieve a better quality at low cost.

(4) Design of experiments to investigate the factors.

(5) Implementation of experimental design in the industrial environment.

(6) Collect samples and analyse the industrial data after implementation to determine the important factors.

(7) Develop models for predicting process behaviour.

The flowchart of this methodology is shown in Figure 1.1

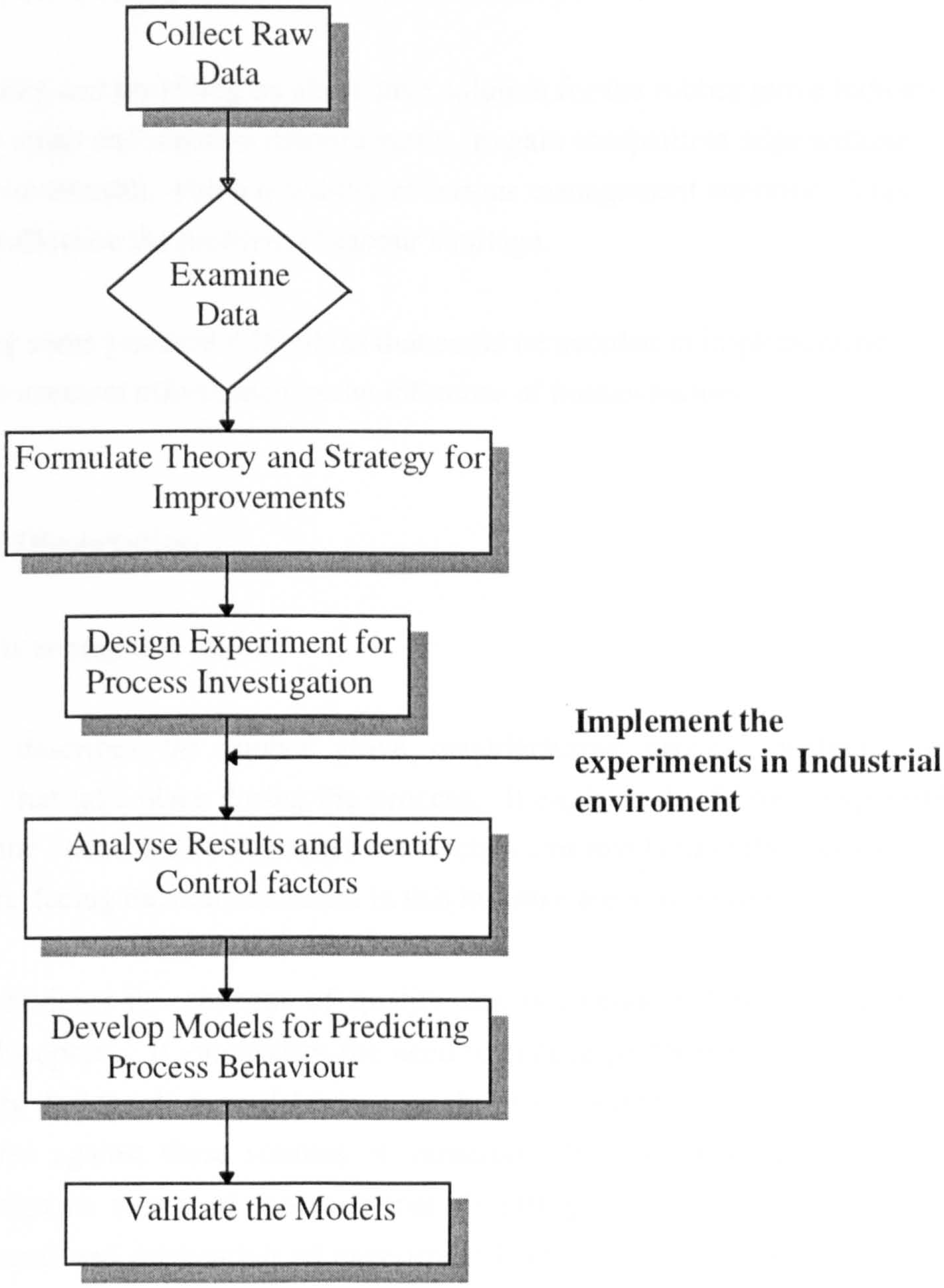


Figure 1.1 Methodology of the Study

1.5 Contributions of this Study

(1) Providing and demonstrating a methodology of robust design experiments for the rubber glove manufacturing process environment.

(2) Enhancing the understanding of the rubber glove manufacturing process.

The additional knowledge gained would make monitoring of the process easier because unnecessary adjustments to non-influential factors are not made.

(3) Demonstrating and providing an alternative solution for the rubber glove industry, particularly small and medium manufacturers, to gain competitive edge without any capital investment, which is worthy of serious management attention. This should also alleviate the problem of labour shortage.

(4) Highlighting some practical difficulties that could be avoided in implementing quality improvement efforts such as the influence of human factors.

1.6 Outline of Dissertation

This thesis is arranged as follows.

Chapter 2 describes the rubber glove manufacturing process, including the chemical reactions that take place during the process. It explains the factors responsible for the stability of the latex. It also describes the mechanisms involved in the formation of latex film. Problems facing the manufacturers in this industry are also highlighted.

Chapter 3 reviews the concept of quality improvements and the evolution of quality control philosophies. It emphasises the need to reduce performance variation in a product and process design. It then elaborates on the main causes of product variations and countermeasures against these sources of variation. It introduces the concept of robust process design as a way of lowering manufacturing cost. It then reviews the historical development and application of experimental design. Criticisms of Taguchi's approach are discussed.

Chapter 4 develops the strategy and planning for integrating robust concepts and experimental designs. An industrial rubber glove manufacturing process is used to illustrate the ideas presented in chapter 3. Details of how the experimental layout may be designed are discussed. Fundamental principles involved in the design are also considered. Guidelines for implementing the experiment in the industrial environment are also outlined.

Chapter 5 discusses the technique used in analysing the preliminary data and data collected from the industrial experimentation. It elaborates on how variability is related to the settings of process parameters and provides guidance for selecting process parameters levels that minimise variation. Finally, it highlights some difficulties in the results due to some common adjustment among the responses.

Chapter 6 discusses the issues associated with the practical implementation of quality programmes. It also highlights the role of human factors in quality improvement efforts. Also, the benefits of design of experiments and the spin off of quality improvement programmes are discussed.

The final chapter presents a general discussion of the findings and how they might be applied to the natural rubber industry in Malaysia and also makes suggestions for further study.

CHAPTER 2

MANUFACTURING OF NATURAL RUBBER GLOVES

2.1 Introduction

Currently, the major area of manufacturing using natural latex is the production of dipped goods. These products include rubber gloves of all kinds, balloons, teats and soothes, bladders, catheters, condoms, rubber tubing, etc. Natural latex has the outstanding property of being able to form strong films which can tolerate rapid drying (Gazeley et al.,1988).

The two dipping techniques which are commonly used in the production of examination gloves are the straight dipping method and the coagulant dipping method. The latter method is the most widely used in industry. This method has two different systems of operation, namely an automatic continuous batch system and an automatic chain driven system. The latter system of operation is the most commonly used in the Malaysian rubber glove manufacturing industry. This chapter will only discuss the coagulant dipping method which was used as a case study.

2.2. Latex Compounding Process

Compounding processes transform raw natural rubber (latex) into a range of materials suitable for application. These changes are accomplished by addition of a number of ingredients to the concentrated latex according to the required formulation. The compounding formulations used in specific products vary slightly from factory to factory. The main objectives of compounding are to obtain the desired processing characteristics and product properties.

The ingredients to be added are ground to the finest possible dispersions before being incorporated in the latex. Coarse particles can make processing difficult by setting in the dipping tanks and may result in defectives product (Pendle and Gorton, 1980). Only soft water or de-ionised water is used in the compounding process to reduce coagulums in the latex. During the mixing operation, low agitation has to be observed in order to maintain mechanical stability and to minimise the formation of bubbles. Blackley et al. (1982a) reported that the ability of a latex to withstand colloidal destabilisation under mechanical influences is important for practical purposes. For the coagulant dipping process, stabilisation of the compound is achieved by using a combination of an alkaline and a fatty acid soap containing 8 to 12 carbon atoms. This latex is then stored in pre-ageing tanks for 24-48 hours before it is used in the production line. This is referred to as the maturation process (Gazeley et al., 1988). A number of reactions take place during that time (Gorton, 1978). The detailed colloidal stability of ammoniated latex will be discussed in section 2.6.1.

In general, the main additives added are stabilisers, vulcanising agents and antioxidants. The most commonly used antioxidants are those that have phenolic structures. Various studies of the effects of different types of antioxidants such as amine derivatives and styrenated phenols have been reported (Gorton, 1978). The stabilisers used for latex compounding are the most important additives because they usually have the greatest influence on latex stability. Even though natural latex already possesses its own stabilising materials, protein and soaps, the stability of the compound has to be increased so that the compound latex can withstand agitation during dipping. However, this increased stability cannot be obtained at the expense of gelation. In this respect, the widely used fatty acid soaps are ideally suited, as they give significant increases in mechanical stability without inhibiting the gelation. Sulphur was the first vulcanising agent used in the first commercial elastomer, natural rubber. Its continued popularity is due to low price, easy availability, fast vulcanisation, minimal interference with other compounding ingredients and an excellent balance of vulcanising properties. Another factor is the versatility with which the rate of cross linking and final vulcanise properties can be varied by changes in the type and proportion of the accelerator.

2.3 Dipping Process

Dipping is used to form a rubber deposit around the outside of a former. The dipping process line under investigation is part of a natural rubber (examination) glove manufacturing plant, and is presented schematically in Figure 2.1. The process begins with the cleaning of the formers and ends with the stripping of the gloves from the formers. The cleaning operation involves the washing of formers with an acid solution. They are then neutralised with an alkaline solution followed by rinsing and drying in the oven. The cleaned formers are dipped into the coagulant tank at a predetermined angle for an appropriate time and withdrawn slowly from the dipping tank. Rotation of the formers is usually continued through a full revolution throughout the whole process. Both solutions, the coagulant and latex respectively, are kept in motion and circulated from the top to the bottom of the tank in order to prevent skinning, creaming and sedimentation by means of the automatic stirrer.

The coated formers are passed through an oven prior to dipping into the latex tank. The duration of dwelling time of the formers in the latex tank is dictated by the thickness of deposit required. They are dried in an oven again before the beading operation begins. The bead is made by rolling down the topmost portion of the deposit on the former mechanically by means of small rotating rollers. This is then followed by the leaching operation, where the water is maintained between 60-80 °C. The formers are then sprayed with cold water before dipping into the slurry or wet powdering tank. Finally, the formers are dried and vulcanised by passing them through oven compartments with different temperature profiles before the gloves are stripped off. The dipping cycle is normally repeated continuously for 24 hours a day, up to a maximum of 300 days a year. The whole process is driven by an automatic constant speed conveyor belt.

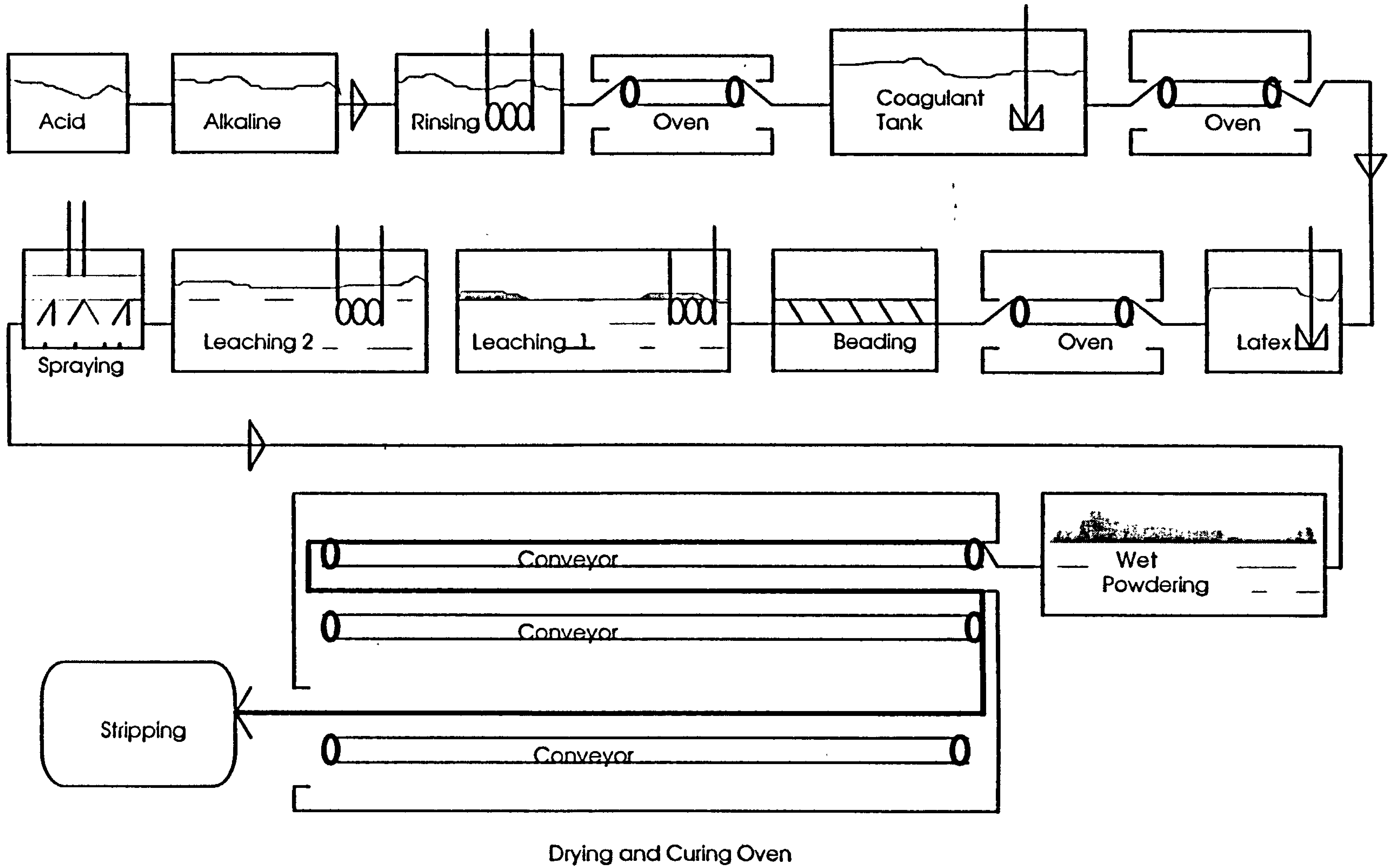


Figure 2.1 Flow Diagram of the Rubber Glove Manufacturing Process

2.4 Sequence of Operations

2.4.1 Former Cleaning

Prior to dipping, the formers are washed and cleaned. Proper cleaning is important. There are various ways of cleaning the formers, namely using chemicals such as strong inorganic acids or alkalis, mechanical scrubbing or brushing. The former is then neutralised, rinsed in hot water, and then dried in an oven prior to dipping into the coagulant. The presence of grease on the surface of a former leads to thinning and even to the complete absence of deposit in that region. Particles of dust and dirt promote pinholes and weak spots leading to subsequent tearing. Former cleaning ensures dust free and good wetting conditions.

The formers used in the latex dip, are normally made of porcelain The advantage of using porcelain is that it is resistant to chemical attack and has a high heat retention capacity. These could either be glazed or unglazed. Unglazed materials are especially suitable for use with coagulant solutions, since the former can then absorb substantial amounts of the solution into the pores, without having to rely solely upon the small quantity which adheres to the surface by way of viscosity. However, glazed formers are preferred in most instances, because they impart a smoother surface to the subsequent deposit and present less difficulty in the removal of the product after drying and vulcanising. They are also easier to clean.

2.4.2 Coagulant Dipping

At this stage, the formers are dipped into the coagulant tank for 16 seconds so that a thin and uniform layer is deposited on the surface of the formers. This can be achieved by a slow immersion and withdrawal of the formers followed by mechanical manipulation and fast evaporation of the coagulant. The former is then dried in an oven before dipping into the compounded latex. A typical coagulant formulation comprises a mixture of calcium salt, water or alcohol, a wetting agent and an anti-tack agent. The tank is normally fitted with a stirrer so as to prevent sedimentation of the chemicals. A screen is also used to retain air bubbles and traces of coagulum which might have formed.

2.4.3. Latex Dipping and Gelling

In the latex dip, the formers are immersed into the latex compound for a predetermined time followed by a slow withdrawal of the formers so that a smooth and uniform thickness of deposit is obtained. The dwelling time normally varies between 5-20 seconds. The gelled deposit is then dried in an oven. Destabilisation of the compounded latex takes place at this stage. A detailed description of this reaction will be dealt with in section 2.6.

The latex dipping tank is fitted with a water jacket chiller system in order to maintain a constant temperature. Also, it is effective in retarding the rate of pre-vulcanisation and in maintaining constant viscosity and stability (Blackley, 1966). A sieve is also attached at one end of the tank so as to retain air bubbles and traces of coagulum. A stirrer is normally attached so as to keep the compounded latex in motion, circulating from the top to the bottom of the tank and back again. The tanks are usually made of stainless steel.

2.4.4. Beading and Leaching

Once the basic form has been achieved, the gloves may be beaded. This involves rolling down a thin film of rubber deposit from the cuff, using small rotating rollers. The gloves are then leached in two tanks filled with hot water. The leaching water is continuously replenished in order to maintain its cleanliness. Leaching removes water soluble materials and hydrophilic components from the latex film or residues such as coagulant and soaps. Removal of these materials improves film clarity, prevents the formation of surface blooms during storage, and lowers the water absorption of the product, thus improving its electrical resistance (Pendle and Gorton, 1978). Sufficient time for leaching is required to give a good quality product.

2.4.5. Drying and Vulcanisation

At this stage, drying is required to reduce the water content in the gel to the lowest possible value as quickly as possible. This may be done by direct heating, by the use of infra-red rays, by hot air or by steam. Vulcanisation is then required to give the product the desired strength after drying. Final drying and vulcanisation is usually performed at temperatures between 100-140 °C. In this process, drying and vulcanisation temperature is held between 80-150 °C. In practice, however, drying and vulcanisation take place together.

2.4.6. Wet Powdering

In the process being considered, after leaching, the former with latex deposit is immersed into a slurry of powder. A wide range of dusting powders can be used including specially treated corn starch, magnesium carbonate and calcium carbonate. This process employs treated corn starch as the anti-tack agent. They can be applied dry or wet (as a dispersion in water). Powdering is necessary to prevent the gloves from sticking after removal from the formers.

2.4.7. Curing, Stripping and Inspection

After the wet powdering process, the latex film is cured in an oven. During this stage of the process, the latex film is dried and vulcanised to the required tensile properties. After the curing process, the gloves are stripped from the former and manual stripping is normally employed. This is the current practice used in the processing plant under study. During stripping, the gloves are turned inside out. This completes the dipping process.

After stripping visual inspection, which is the most labour intensive stage of the process, is followed by an inflation test to detect pinholes and weaknesses in the glove wall. The level of inspection will depend upon the level of defects occurring in the production. A 100% inspection level, that is every single glove must be inspected, is required if the level of defects is higher than the required acceptable quality level (AQL) which is defined as the percent non conforming that product can be considered satisfactory by the customers.

2.4.8 Tumbling and Packing

The stripped gloves are tumbled in a dryer for a certain period of time. The main purpose of this process is to remove excess powder. The gloves are then packed into dispenser boxes, normally 100 pieces per box. The current practice adopted in this particular plant, is to weigh 780 grams of gloves which will approximately account for 100 pieces of gloves, assuming each piece weighs about 7.8 grams. The dispenser packages are then packed into despatch cartons.

2.5 Composition and Some Latex Properties

Natural Particles in Latex

Natural rubber (NR) latex concentrate is a colloidal dispersion of NR particles in an aqueous medium. The rubber particles are usually spherical in shape with diameters ranging from about 0.02μm to 3 μm, but in latex from certain mature clones, the particles may be pear shaped. The rubber contained in the particles is non-water soluble and occurs as molecular aggregates. For instance, a rubber particle of diameter 0.1 μm would contain about 290 rubber molecules if the molecular weight is 10^6. The rubber hydrocarbon is predominantly cis-1-4-polyisopropene. An interesting feature to note is that fewer than about 5% of the particles have diameters larger than 0.4μm, yet this small percentage of particles contain some 90% of the rubber in the latex (Archer et al., 1963; Cockbain and Southorn 1962).

Serum Phase

The serum phase of latex concentrate contains a wide variety of non-rubber substances. The majority of the constituents are proteins, amino acids, carbohydrates, some higher fatty acid soaps (containing 10 to 12 carbon atoms) and a range of organic and inorganic salts. The salts in latex concentrate serum have been analysed and fourteen anions have been detected. These include carbonate, acetate, malate, succinate and citrate as the major components and smaller amounts of formate, α-glycerophosphate, glucose-1-phosphate, phosphate, oxalate, chloride, sulphate, hydroxide and propionate.

The predominant cation (positively charged ion) present in ammoniated concentrate is ammonium. Of the metallic cations present, the most important are potassium, magnesium, iron and copper together with any zinc that is added during the production process. Chen (1981); Chen and Ng, (1984) reported that NR concentrate produced in Malaysia contains approximately the following amounts of these elements: 1800 parts per million potassium; 30 parts per million magnesium; 5 parts per million iron and 3 parts per million copper (based on total solid). Potassium which is of botanical origin is in the largest concentration. The potentially deleterious element copper (a pro-oxidant) is present only in trace amounts and iron content is of similar amount.

2.6 Physical and Chemical Reactions

A comprehensive understanding of the factors influencing the behaviour of natural latex is not yet available (Gazeley et al. 1988). Nevertheless, the present state of the chemical and physical processes related to product manufacture have been established.

2.6.1 Compounding- Latex Stability

In all latex processes, a stable colloidal system is maintained until, at the required time, it is made unstable and converted to a solid product. The stability of a polymer latex may be divided into two aspects: mechanical stability and chemical stability.

Mechanical stability is the term used to describe the resistance to those mechanical influences which increase the number and vigour of collisions between particles and hence the tendency of the latex to coagulate. Chemical stability is defined as the ability of the latex to resist the effects of chemical destabilising agents.

In ammonia-preserved latex concentrates, the rubber particles are covered by a complex film comprising proteins, higher fatty acids soaps (arising from hydrolysis of some lipids) and lipids mainly neutral lipids. Based on classical theory, the factors responsible for stabilisation are as follows:-

(1) Electrical charges on the particles
(2) Degree of hydration

A single particle in ammoniated latex is depicted in Figure 2.2. Under alkaline conditions, at pH 9 to 10, almost all the acid groups of the soaps and proteins are ionised, thereby giving a negative charge to the particle. Also attached to the surface are a few cations (positive charges), for example ammonium ions, and a certain amount of water. It is these electrical charges on the surface of the rubber particles that are mainly responsible for the colloid stability of the latex. In simplified terms, electrostatic repulsion between two neighbouring particles prevents them from coming too close to each other. The detailed mechanism of repulsion is more complex than this. All molecules and ions outside the dotted line in Figure 2.2 can move independently of the particles. The ions in the immediate neighbourhood of the dotted line are predominantly positive ions (cations) surrounding each particle (that is, the electrical double layer). When two particles approach each other, the electrical double layers associated with the particles overlap and this results in repulsion between the particles. This repulsion is commonly referred to as electrical double layer repulsion. According to Cockbain (1948), repulsive and attractive forces between charged bodies are not the only ones operating, since in that case adhesion of similarly charged particles would never occur, even when the charge was small.

The basic cause of adhesion between such particles is that the spontaneous absorption of soaps and proteins contains groups possessing two electrical charges (dipole moments), as well as fully ionised groups by a surface. The dipole moments may be a permanent feature of the molecules or ions. The interaction between dipoles leads to an overall attraction: the so called Van der Waals attractive force.

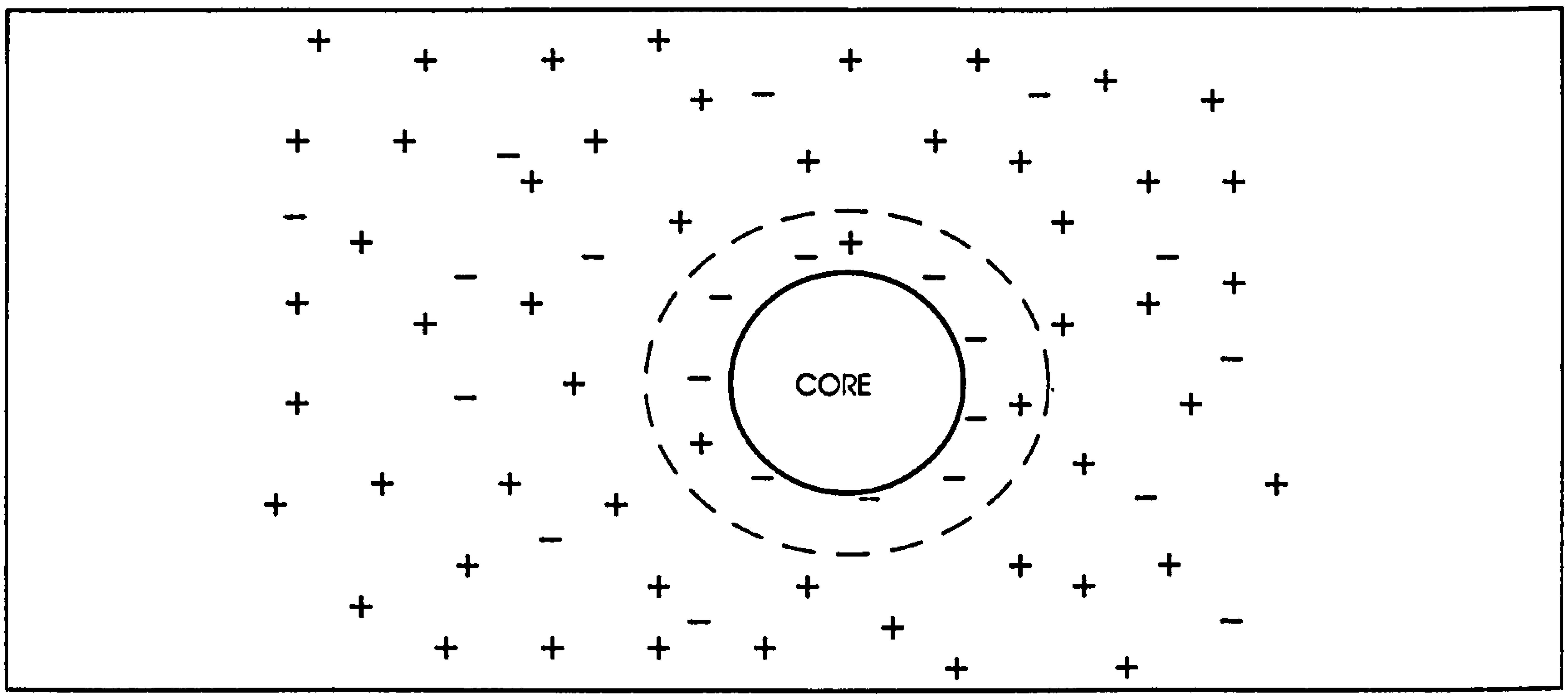


Figure 2.2 Diagrammatic Representation of a Rubber Particle in Ammoniated Latex (Cockbain, 1948)

Addition of neutral salts to latex, for example sodium chloride, increases the concentration of sodium ions in the ionic atmosphere and, owing to the "shielding" effect of these ions, the negatively charged particles can approach one another more closely. If the approach is close enough, the attraction forces mentioned above are sufficiently strong to cause adhesion. A certain amount of sodium ions may actually be adsorbed at the surface, in which case the electrostatic repulsion between the particles is reduced, and adhesion facilitated. Both the shield phenomenon and the adsorption effect increase substantially with increasing valency of the added cation (Cockbain, 1948).

A second factor partly responsible for the stability of latex is the degree of hydration of the particles. The coagulation of latex by solvents with a high affinity for water is attributed to dehydration of the interfacial soap-protein film. Hydration of the particles can also be diminished by the addition of solid powders with a high water affinity, or by suppressing the ionisation of the carboxyl groups in the adsorbed film (ionised groups are particularly strongly hydrated).

As regards the mechanism of stabilisation by hydration, it has been postulated that a layer of water, several molecules thick, can be "bound" at the interface, thereby promoting stability by a mechanical "buffer" action during collision of the particles. The extent to which hydration occurs is unknown. However, it is believed to depend very much upon the nature of the soap-protein film which is a result of the spontaneous absorption of molecules at the particle interface. Adsorption processes are almost invariably accompanied by a reduction in interfacial free energy.

2.6.2 Destablisation of the Latex

Destabilisation refers to the process which destabilises a latex to such an extent that the particles merge together to form a single larger particle (coalesce). Destabilisation may occur in three distinct forms, depending on the nature of the product which is formed. These are: gelation, when a continuous uniform gel is obtained; coagulation, when lumps of coagulum are formed; and flocculation, when a mass of small flocs is obtained. Natural rubber latex could be destabilised by physical or chemical means. The former include heating, freezing, mechanical agitation and removal of water by evaporation. Chemical means of destabilisation include addition of acids, salts and water-miscible organic solvents.

Physical Means of Destabilisation

Thermal Effects

(a) Low temperature. Most lattices will undergo fairly rapid destabilisation in the frozen state.

(b) High temperature. Depending on the stabiliser present, most lattices are fairly stable up to about 90 °C but will undergo rapid destabilisation on boiling, or prolong heating. However, lattices stabilised by non-ionic stabilisers are the major exception. Depending on the cloud point of the stabiliser, destabilisation can occur at around 35-40 °C.

Mechanical Agitation

The effect of mechanical agitation (for example friction, shear and turbulence) is to increase the frequency of particle collisions as well as the velocity of impact on collision. Over a prolonged period of time, this will cause lowering in the stability of the latex, with consequent partial destabilisation (Gorton and Pendle 1978).

Evaporation

If latex is exposed to the atmosphere without any means of preventing the loss of water by evaporation, it is observed that a skin will be formed. Loss of the "dispersion phase" therefore causes latex destablisation. The effect becomes more pronounced at higher concentrations of latex. This is in a way helped by the creaming of rubber particles to the surface.

Chemical Destabilising Agents

Acids

Acids are powerful coagulating agents for anionic lattices. They function principally by reversing the ionisation process of anionic stabilisers, thus reducing the ionic stability of the rubber particles. Although there are many types of acids, the suitability of any one acid depends on various factors, such as price, side effects, ease of handling and administration, etc.

Electrolytes-metallic salts

These are basically divalent or trivalent metallic ions, and can act on anionic lattices in two ways:-

(a) Formation of metallic hydroxides, which are surface-active. Under alkaline conditions, the added metallic ions react to form metallic hydroxides, which will absorb the stabilisers from the latex particles. The latex loses its stability in this way.

(b) Formation of insoluble metallic soaps. Latex destabilisation is effected by the "pulling together" of rubber particles by the reaction of the metallic ions with the soap ions. Blackley et al.(1982), Blackley and Haynes, (1981) reported that addition of fatty acid soaps to natural rubber latex increased its mechanical stability significantly. On the other hand, addition of calcium nitrate effectively reduced its mechanical stability (Blackley et al.,1982a). During the dipping process, reduction of latex stability takes places when the coagulant layer which contains calcium nitrate (inorganic electrolytes) is immersed in the latex compound. This type of reaction is visualised to take place at the surface of the rubber particles. The reaction can be represented as follows.

$$2R-COOH \;+\; Ca(OH)_2 \;\rightarrow\; Ca(R-COO)_2 \;+\; 2H_2O \qquad (2.1)$$

The coefficients in equation 2.1 indicate the number of molecules of reactant and products. The equation says that two molecules of $R-COO^-$ react with one molecule of Ca^{2+} to produce one molecule of insoluble salt and two molecules of water. The Alkyl group is represented by the symbol R. Organic acids are known as carboxylic acids and their characteristic function group $COOH$ is referred to as the carboxyl group. Acids in the family $R-COO^-$ where R is an alkyl group, are called fatty acids. When chemical interaction between the coagulant and the latex occurs, the metallic ions Ca^{2+} which are positively charged, react with the fatty acid anions which are negatively charged to form insoluble soaps. Also in the presence of Ca^{2+}, the particle surfaces are compressed hence particles repulsion is reduced. Thus, latex loses its stability in this way. Consequently, a continuous uniform gel/layer is formed.

Solvents

(a) Polymer-miscible solvents. Absorption of solvent for example Dutrex oil, benzene, etc. by the rubber particle results in "swelling" of the particles, with consequent decrease in the percentage particle surface area covered by soap. Hence destabilisation occurs.

(b) Serum-miscible or water-miscible solvents. Addition of such a solvent in this case cause a dehydration of the surface layer, thus removing the "buffer" required for stabilisation. This method of stabilisation is particularly suitable for lattices stabilised by non-ionic stabilisers, for example alcohol, acetone, etc.

2.7 Formation of Latex Film During Coagulant Dipping

One of the most important aspects of the coagulant dipping of rubber lattices is the latex film (deposit) formation because of its industrial importance. Although considerable literature exists on the subject of coagulant-dipping of rubber lattices, much of these have been concerned with the dependence of the deposit thickness upon the dwelling time of the former in the latex (Stewart, 1973, Gorton and Iyer1973; Gazeley et al., 1988; Blackley et al.,1982; Cockbain, 1948). Few studies of the process have been made with a view to providing a deeper understanding of the mechanism of the process.

The formation of latex film is a process of transformation, from the colloidal dispersion into a continuous polymer film (Vanderhoff, 1977). Formation of the latex film (deposit) involves drastic reduction of the colloid stability of the latex by the cations of the coagulant. This is due mainly to chemical interaction between cations of the coagulant and some of the anions (negatively charged ions) adsorbed at the rubber-aqueous phase interface. This plays a vital role in the initial stability of the latex (Stewart, 1973; Gorton and Iyer, 1973; Gazeley et al.,1988; Cockbain, 1948). On the other hand, Blackley et al. (1982) argued that the calcium ions did not react with the adsorbed higher fatty-acid soap anions but rather compress the electrical double layers which surround the rubber particles. He also suggested that the principal factors responsible for the colloid stability of the latex is not the adsorbed higher fatty-acid anions, but other factors such as adsorbed proteins and their hydrolysis products. According to Blackley et al. (1982), none of the empirical equations that have been proposed to represent dêposit thickness as a function of dwell time is satisfactory, in the sense that they are not capable of describing all cases.

In the coagulant dipping process, as soon as the former with the coagulant deposit comes into contact with the latex compound, a latex film is formed almost instantly (gelation). The calcium ions cause gelation by reducing the charges on the particles, causing collapse of the electrical double bond layer and hydration layer around the rubber particles. This is the first film formation. The presence of the insoluble calcium in the gel/film indicates that chemical reaction has taken place between the calcium ions of the coagulant and the negatively charged ions of the fatty acids in the latex. The coagulant has to be made soluble and pass through this film before the second rubber deposit can be formed. The aqueous phase between the particle interface in the film serves to dissolve the coagulant ions. These must then diffuse through the film out to the latex to form more film. A concentration gradient is thus set up which depends on the rate of diffusion of the coagulant ions. That is, as the deposit (film or gel) gets thicker, the coagulant concentration drops due to serum dilution, and coagulant ions take longer to reach the latex. The diffusion of the calcium ions outwards from the former surface is retarded by the presence of the rubber particles (Gorton and Iyer 1973; Gazeley et al., 1988). The amount of calcium which diffuses from the former into the bulk of the latex is very little. According to Gorton and Iyer (1973), the thickness of latex film by coagulant dipping depends on the ionic diffusion of the coagulant and the pore size of the film. Similar findings was reported by Blackley et al. (1982) whereby the rate at which the film builds up is governed by the rate of diffusion of the coagulant into the latex.

Figure 2.3 shows a cross-section of film layers during the dipping process. The first deposition of latex which develops immediately as the coagulant comes into contact with the latex compound is depicted in region II. As the former dwells in the latex compound, the second latex deposit develops in region III due to diffusion of the coagulant in region II into the latex in region IV. Region I represents the dry deposit of coagulant; region II, the first deposit and region IV, the bulk latex compound (Gorton 1967, Gorton and Iyer,1973; Gazeley, 1982; Gazeley, 1988).

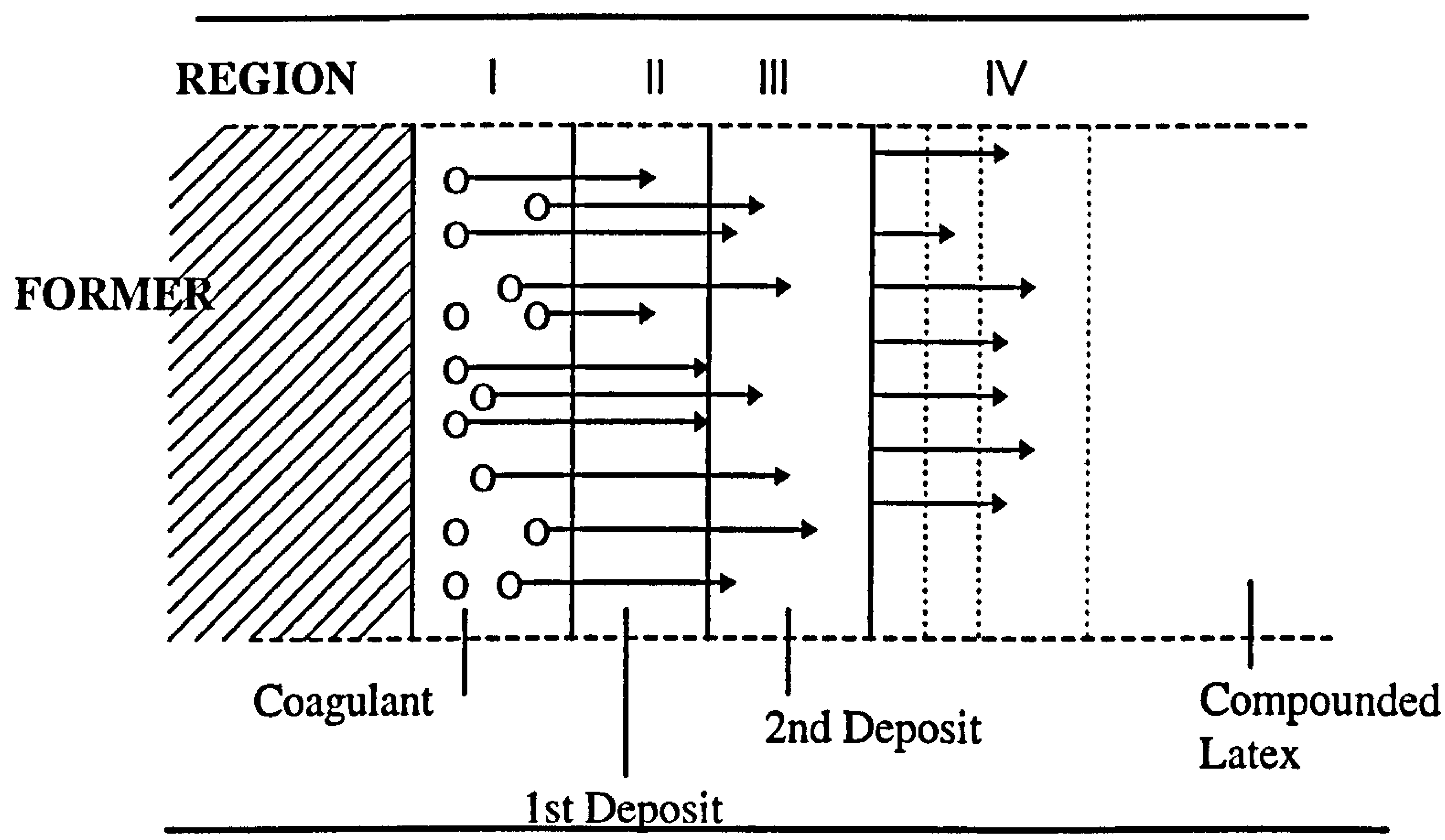


Figure 2.3 Formation of Latex Deposits by Coagulation Dipping

2.8 Drying and Vulcanisation

Although the distinction between the drying and vulcanisation processes is quite obvious, in practice, this distinction is unnecessary as both processes happen simultaneously but at different rates (Pendle, 1995). International Standard Organisation (ISO) 1382 (First edition, 1972) defines vulcanisation as a process in which rubber, through a change in its chemical structure such as cross linking, is converted to a condition in which the elastic properties are conferred. In other words, it consists of the formation of a molecular network by a chemical binding of independent chain molecules. The resulting rubbers retract forcibly to their approximately original shape after large mechanically imposed deformations. Vulcanisation, therefore is an intermolecular reaction which increases the retractive force and reduces the amount of permanent deformation remaining after removal of the deformation force; that is it increases elasticity while decreasing plasticity.

According to the theory of rubber elasticity (Flory, 1953), the retractive force resisting a deformation is proportional to the number of network-supporting polymer chains per unit volume of elastomer. A supporting chain is a segment of polymer backbone between network junctures. An increase in the number of junctures gives an increase in the number of supporting chains. In an unvulcanised high polymer, above its melting point, only molecular chain entanglements constitute junctures and their number per molecule increases with molecular weight. Vulcanisation usually produces network junctures by the insertion of chemical cross-links between polymer chains. These cross-links may be chains of sulphur atoms, single sulphur atoms, carbon-carbon bonds, polyvalent organic radicals, or polyvalent metal ions.

Dipped products are usually dried and vulcanised in hot-air ovens. The deposit on the former is often partly dried at a relatively low temperature about 80-90 °C before the final drying stage. This preliminary drying is particularly important with thick-walled products because of the risk of blister formation due to rapid volatilisation of water, if the former is subjected directly to temperature above 100 °C. Cross linkage of rubber particles takes place on drying of the latex deposit. The particles are brought closer together, forming a vulcanised film as illustrated in Figure 2.4. This enables the strength and elastic properties inherent in raw rubber to be fully realised. Final drying and vulcanisation is usually carried out at temperatures of 100-140 °C. Brown (1956) reported that film formation in many polymer emulsion systems occur concurrently with the evaporation of water, and is complete when water evaporation is complete.

The rate of drying of latex films was studied by Vanderhoff et al.(1973) and can be divided into three stages. In the initial stage, the rate is constant, the particles are free to move about with their characteristic Brownian motion, that is in random motion, and the rate of water evaporation is unaffected by their presence. Then, at the intermediate stage, the water-air interfacial tension forces the particles into irreversible contact with one another, causing them to coalesce. Brown (1956) investigated the mechanism for film formation and claimed that the pressure forcing the particles together is increased by the force arising from the water-air interfacial tension, until the stabilising layers are ruptured and polymer-polymer contact is formed. During the final stage, the particles are grouped together, and the remaining water evaporates by diffusion through capillary channels or through the polymer itself. Figure 2.4 illustrates these three stages schematically.

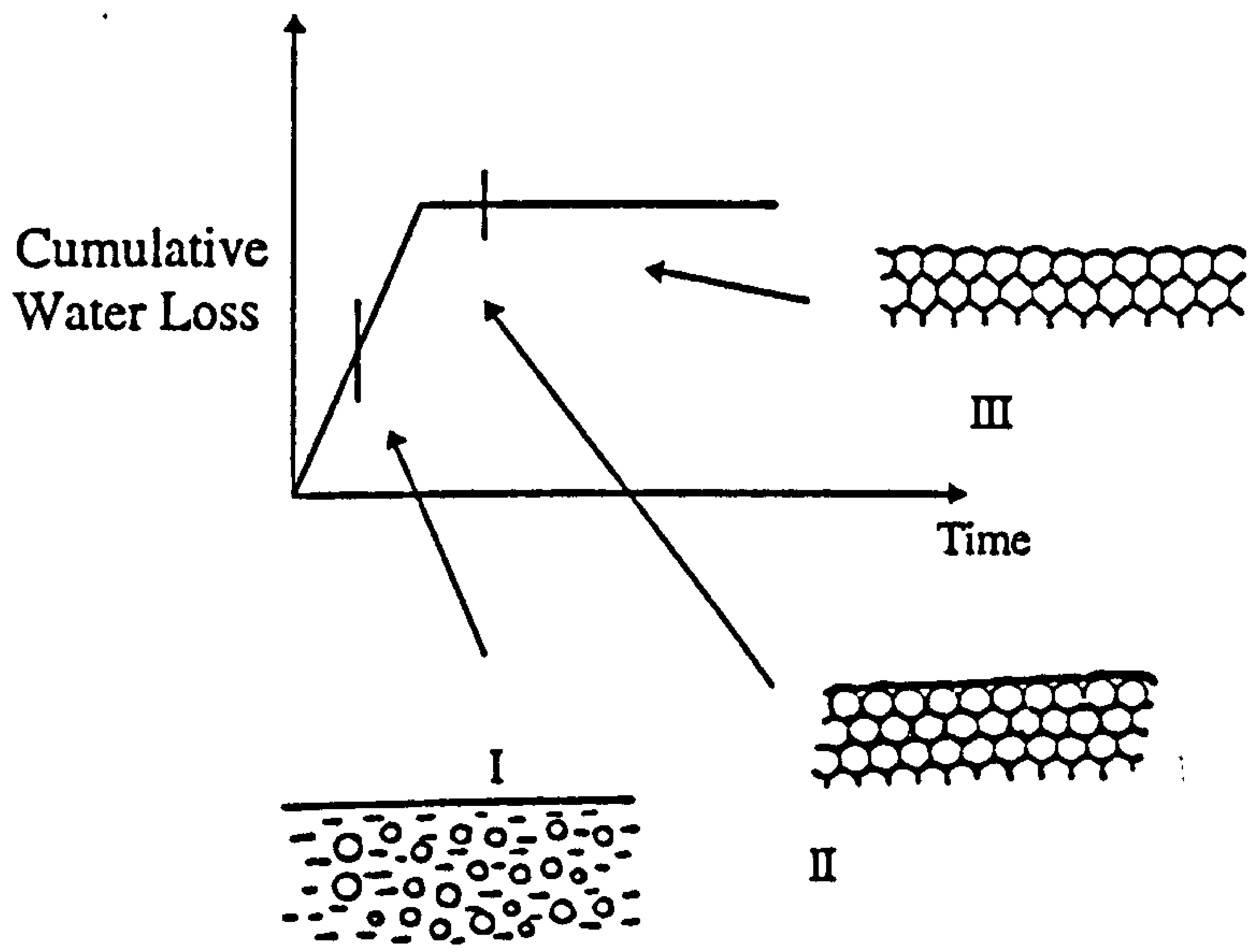


Figure 2.4 Schematic Representation of the Three-stage Drying Process

2.9 Problems Faced by Manufacturers in the Rubber Glove Manufacturing Industry

The major problems faced by manufacturers in this industry as reported by the rubber industry task force (RITFO) 1990 were first labour shortage. In Malaysia, the shortage of industrial manpower is increasingly becoming serious as the industry continues its rapid expansion. This has resulted in head hunting or job hopping of talented or highly qualified personnel, and this problem has discouraged many companies from providing training for their staff. This problem is especially serious among quality control engineers, because of the significant shortage of supply over demand for such engineers. Also as discussed earlier in chapter 1, although there was a rapid increase in production cost, the glove prices remained unchanged.

Other production related difficulties are as follows. Historically, gloves manufacturing has been associated with craft oriented industry. Due to the nature of the industry and the complexity of the technology in the processes, manufacturers have very limited understanding of the process involved. Many of them are not well-versed with quality control techniques that can be used to improve their processes and product quality. The management of these producers did not appear to understand the content and purpose of good manufacturing practice requirements of the Food and Drugs Administration (FDA). Companies that intend to export to the USA must conform to these requirements, otherwise they will be black listed by the FDA. If no improvements were made the company will be banned from exporting to the USA. According to the Federation of Malaysian Manufacturers (FMM) survey the number of companies that are interested in taking up quality control activities is high. What is preventing them from carrying out quality activities is the lack of staff who can carry out quality control in factories followed by insufficient understanding of quality control methods and a high rate of personnel turnover. The current shortage in staff responsible for quality activities is a major obstacle to advance in this field. A survey also conducted by the FMM revealed that the awareness of quality management amongst management was very low. This awareness was about 10%. Many of them have a passive attitude towards undertaking quality management. This is because they have insufficient appreciation of the benefits that quality management brings about in improvement of technology. Most of them are interested in short-term benefits.

According to the RITFO survey 1990, the use of statistical process control tools such as control charts was not prevalent, as only one company was noted to use these tools. The only statistical tool commonly used was lot acceptance sampling. Manufacturers relied solely on final product inspection to fulfil customers' specifications. Similar findings were reported by the Japan International Co-operation in 1993. Many factories limit the function of quality control to merely screening out defective products. It was noted that inspection processes required a large work force, especially if 100% inspection is practised. Clearly, as production yields increased further improvement will be more difficult.

Recognising these problems, steps are needed to improve production processes further to levels where labour for inspection and sorting can be reduced . This would be necessary to ensure longer term survival of the industry, especially in the event of increasing labour cost and competition from lower cost producing countries. Hence manufacturers would have to utilise more specialised techniques to make further gains.

2.10 Chapter Summary

In this chapter we describe the process flow of rubber glove manufacturing including the physical and chemical reactions that take place during the process. We only consider the coagulant dipping method and the automatic chain driven system commonly used in the Malaysian rubber glove manufacturing industry and particularly in this case study. We then establish the scope to be investigated. The mechanisms involved in the formation of latex film which has industrial importance during coagulant dipping are also presented. Having established the process involved, we then turn our attention to the problems encountered by manufacturers in this industry. Chapter 3 will review the quality control philosophy and the statistical literature with respect to robust designed experiment for industrial application. It seeks to formulate ways to address issues previously discussed in section 2.9.

CHAPTER 3

LITERATURE REVIEW

3.1 Introduction

In this chapter, we present the concept of quality improvements and its evolution. Next we will discuss performance variations, their sources as well as countermeasures. Later, we will introduce the concept of robust design and review the historical development of designed experiments. We then discuss criticisms of Taguchi's approach to designed experiments for product and process improvements.

3.2 Concept of Quality Improvement and Its Evolution

Quality has been an integral part of virtually all products and services. Quality means different things to different people, and there are many definitions and interpretations of the word. Quality as defined by BS 4778 1987 part 1 is "the totality of features and characteristics of a product or service that bear on its ability to satisfy given needs". This clearly implies that quality is an integration of the following: fitness for use, product performance, conform to specification, reliability, delivery on time, minimum cost/price and shortest possible lead time in response to the customer request. All these must satisfy customers' needs and expectations. Today, quality is the key issue in the success and growth of many multi-national organisations. Buyers, consumers and customers use quality as a major deciding factor in many products and services. Consequently, quality plays a vital role in increasing market share, higher productivity and lower overall costs of manufacturing and service. Moen and Nolan (1987) stressed that quality is improved via the application of new knowledge as a basis for changing the process. Changes are made through corrective action taken based on a better understanding of the cause that affects process performance. As a result these changes permit work to be done better, faster, and easier, decreases in cost accompany the improvements in quality. Thus, effective quality improvement efforts can be instrumental in increasing productivity and reducing cost. This is because analysis of the process involves all members of the organisation and becomes a small part of everyone's job rather than the total responsibility of a few. Since the process is inspected a learning process takes place even though no non conforming products are being produced. Box (1993) further emphasised that quality improvement is about changing things for the better. Companies that are determined to stay in business seek ways to continuously improve quality and focus on ways to reduce the manufacturing cost of their products as well as increasing productivity. They recognised that improving quality reduces costs through the elimination of waste. Improving quality reduces scrap, rework, warranty costs, floor space to hold waste, the work force needed to transport waste, lost capacity currently producing defects and rejected batches etc. Japan has shown the world that improving quality leads to improving productivity at no cost incurred. A Japanese ceramic company, Ina tile knew that uneven temperature in the kiln had caused variation in the tiles size. The company wished to reduce this variation without increasing cost. They tried using the tile formulation in order to reduce the effect of uneven temperature distribution instead of controlling the cause itself (the kiln design). They discovered that increasing the content of lime in the tile formulation reduced the variation. Therefore the problem of uneven tile size was solved by reducing the effect of the cause of the variation (uneven temperature distribution in the kiln). This was achieved by optimising the product and process designs to make the performance less sensitive to the causes of variability. This discovery was a breakthrough for the ceramic industry in Japan.

Traditional quality control is concerned with downstream processes where the focus is on the use of Statistical Process Control charts and inspection schemes such as go/no go gauging, or defective/non-defective sentencing for the lot-by-lot inspection of in-process and finished goods. These "acceptance sampling" systems were designed as a means to pass judgement on large quantities of goods using relatively small samples. The approach has been to detect and rectify defects. This is where most of the effort and resource has been concentrated, since it is at the end of the production line that problems of product quality are visible. However, at this stage of production, opportunities for improvement are severely limited and those that exist are often expensive to implement.

As shown in Figure 3.1, quality activities development has gradually evolved from the downstream to the upstream end of the process. The evolution of quality activities in the United States can be classified into three generations: inspection, manufacturing process control and product and process design improvement. In the 1920s' quality emphasis was in inspection and testing during the manufacturing stage. Later Dodge and Romig developed acceptance sampling methodology as an alternative to 100% inspection. In the 1940s Statistical Process Control became widely acceptable and several textbooks on Statistical Process Control were published. Only in the 1950s designed experiments for product and process improvements were first introduced in the United States. The spread of these methods outside the chemical industry was relatively slow until the late 1970s or early 1980s, when many Western companies found that their Japanese competitors had used designed experiments since the 1960s for process trouble shooting, new process development, evaluation of new product designs and many other aspects of product design, including selection of components and system tolerance. Since the 1980s there has been a rapid growth in the use of Statistical Methods for quality improvement in the United States.

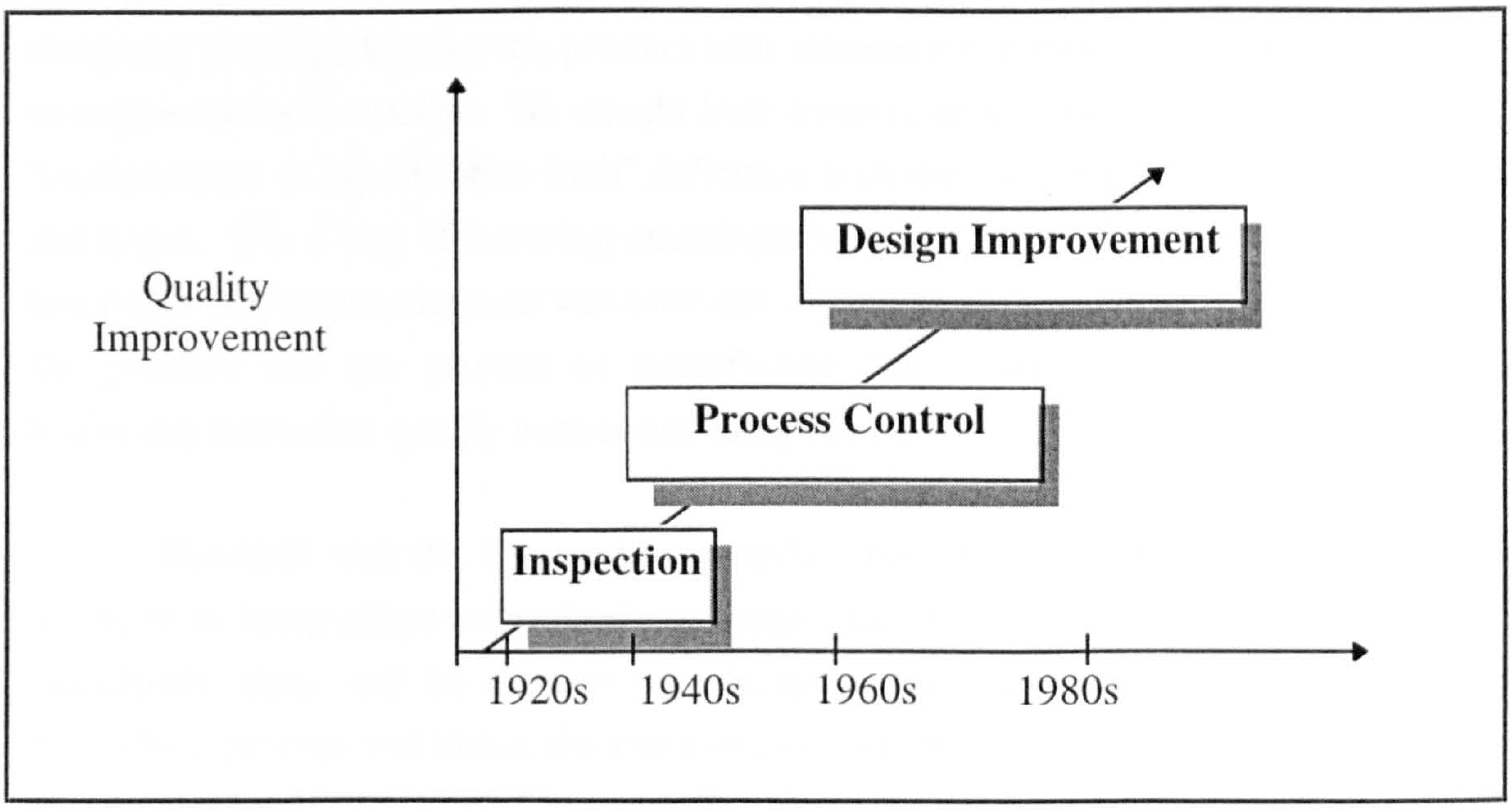


Figure 3.1 Evolution of Quality Control Activities

Quality control inspections alone do not ensure quality products and quality cannot be achieved economically through these efforts (Sullivan, 1984) so that they are no longer a competitive option (Lochner and Matar 1990). This has changed the whole quality control philosophy shifting the focus from downstream to upstream processes. The emphasis now should be on the product development stages (off-line) rather than at the downstream production stage (Gunter, 1987; Sullivan, 1984; Barker, 1986, Box and Bisgaard, 1987; Taguchi and Wu 1980). The difference is to build good quality into the products and processes, instead of trying to inspect bad quality out. The orientation of this approach is on prevention of defects and to do it right first time. But doing things right first time is not good enough. Thereby , we must be sure that we are doing the appropriate thing right first time. By focusing on quality as far upstream as possible, we could design quality products which not only meet initial requirements but continue to delight the customer. So, this will reduce the need for inspection and provide economic gains. This distinction in thinking leads to totally different operational and engineering strategies to improve industrial quality and productivity. According to Box (1993), manufacturing good quality products and increasing productivity at low cost is achieved by learning about processes. To enhance competitive edge in the 1990s, the achievement of quality will require low operating cost and consistent products. Consistent output has low variability and is preferable. Hence, in order to increase profitability and market share, companies are increasingly using high quality and low cost as their combative strategy. From both economical and technological perspectives, to improve quality by designing good quality into the product with minimum variation at low cost is a challenge to engineers and scientists. We should look more closely at our objectives to replace the "conformance to specification limit" definition with the idea of reduced variability around the target. It is a way of lowering manufacturing costs. Box (1985) pointed out that the key factor in Japanese success was their use of statistical methods to "design" quality into the product and the process of manufacture "necessitating much less emphasis on traditional corrective quality control and sampling inspection".

Shewhart was the first person to write about the concept of variability between products as being either within limits or outside those limits. Deming continued work on Shewhart's ideas and he showed manufacturers how to measure the variations in a production process and tackle the cause of poor quality. Deming's philosophy is based on variation reduction for higher productivity. He believed that every employee and manager should be educated and trained and insist on using Statistical Control (SPC) techniques at the same time as encouraging them to prevent defects with rewards (Bendell 1988). One of the main ideas of Deming was to replace final product inspection for defects by a strategy of prevention using SPC (Dale and Oakland 1994). He is credited for introducing statistical quality control to Japan. He had successfully convinced the Japanese management the value of statistical quality control. Though Shewhart techniques were known in Japan before he arrived their use were relatively low. Deming is also recognised for his contribution to the Japanese industrial revolution in terms of bringing the customer and supplier together to work for continuous improvement.

Dr. Genichi Taguchi, a Japanese quality control expert, has been credited for his contributions to Japanese quality engineering. It was through his efforts that Japanese engineering has been able to implement his design philosophy. His concept of quality improvement includes an important measurement model for supporting such a strategy of continuous improvement. The technique addresses a wide variety of engineering problems in product design, evaluation and manufacturing. Thus, the success of Japanese industry in producing high quality product at low cost has been no accident.

In America, Taguchi's quality control philosophy and methods have attracted the extensive attention of quality engineers and statisticians. Many of the early success stories in the United States industry are found in the automotive industry, mainly through the influences of the Ford Motor Company which has been active in promoting the use of Taguchi techniques among its own suppliers as well as within Ford's engineering organisations world-wide. Therefore reducing the variability of manufactured products is the main focus of modern quality improvement.

3.3 Product or Process Performance Variation

Most products or processes have several performance indicators (quality characteristics) that could be identified and measured. However, it is neither economical nor necessary to improve all quality characteristics because not all quality characteristics are equally important. For instance, from the manufacturers' point of view, glossiness of rubber gloves is less important compared to their strength. This is because the latter serves an important function to users, while glossiness is just an aesthetic value. The main quality characteristics that need improvement are the performance characteristics. The clarity of a sound system is an example of a performance characteristic. The ideal value of a performance characteristic is known as the target value. A high quality product performs near the target value consistently throughout the product's life span and under all different operating conditions. For example, a radio set whose sound system varies with weather conditions has poor quality. The variation of a performance characteristic about its target value is referred to as performance variation. The smaller the performance variation about the target value, the better is the quality. For an example samples were taken from a process. They were measured and plotted. If enough samples were taken the resulting pattern would look roughly as a smooth continuous curve. These patterns are known as distributions and are demonstrated in Figure 3.2. The solid line represents the target value and the dashed line represents the average of the measured data. Figure 3.2(C) illustrates the results of corrective actions taken in order to make the product on target and consistent, thus improving quality performance.

Variations occur in every manufacturing process. Analysis of these variations is used as a basis for action to improve the process or product. Hence information gathered from the analysis serves as a source of feedback and an opportunity for product and process improvement. A basic concept introduced by Walter Shewhart in the 1920's for the study and improvement of processes is that variation in a process is due to two types of causes. Common or sporadic causes are those that are inherent in the process hour after hour, day after day. Special causes are those that are not in the process all the time but occur due to special circumstances. This type of variation is also termed "chronic effects". A stable process is one in which variations arise only from common causes. A stable process is in a state of control. This does not mean that there is no variation in the outcome, that the variation is small, or the outcomes meet customers requirements. A stable process simply implies that the variation is predictable within statistically established bounds. On the other hand, an unstable process is referred to as one in which outcomes are affected by both common and special causes. Unstable processes do not necessarily have large variations. It means that the magnitude of variation from one time period to the next is unpredictable.

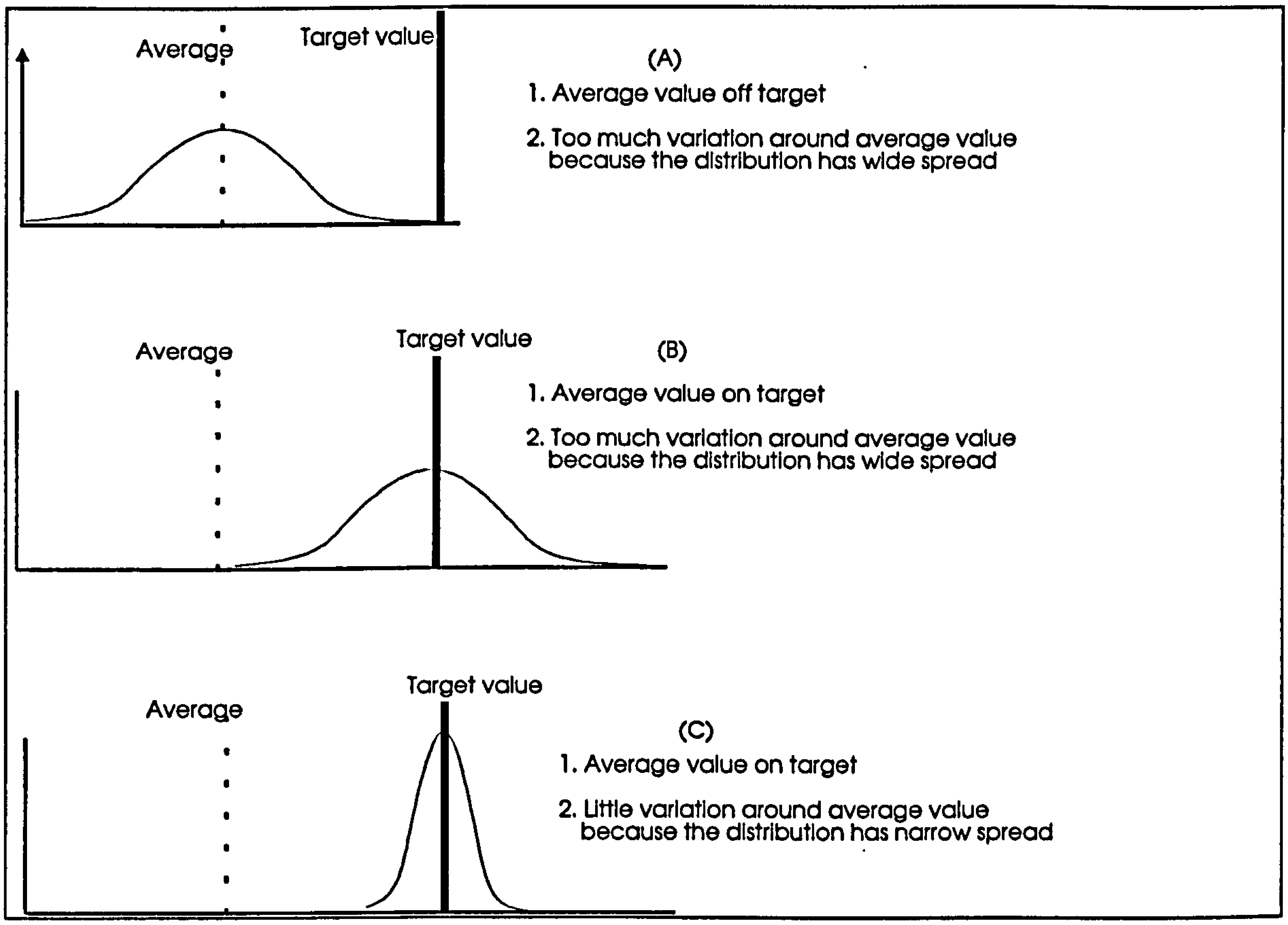


Figure 3.2 Performance Variation Around Target

The proportion of the product's performance which deviates from its target value during the product's life span under different operating conditions, and across different units of the product is an essential aspect of product quality. Kacker (1985) claimed that the proportion of customer satisfaction is inversely proportional to the amount of performance variation. In the author's experience this statement holds true. For example, when a pen does not write smoothly due to inconsistency of the ink flow, one gets frustrated and will not buy that particular brand in future. The main causes of a product variations are due to three factors. They are: environmental factors; product deterioration, and manufacturing imperfections. Fluctuations in environmental variables such as temperature, humidity, and power supply can trigger variations in product performance. On the other hand, product deterioration due to ageing is an important cause of product variation. Examples of product deterioration are: loss of resilience of springs and wearing out of moving parts in a motor due to friction. In a manufacturing process, it is also inevitable to have some variation among different units of a product, due to the manufacturing process.

Each step of the product development cycle has an impact on the quality and cost of a manufactured product. The designs of both the product and the manufacturing process play key roles in determining the proportion of performance variation and manufacturing cost. A product development cycle can be divided into three stages. That is, the product design, process design and manufacturing as shown in Table 3.1 (Taguchi, 1986; Kacker and Phadke, 1981; Kacker 1985).

Table 3.1 Product Development Stages at which Countermeasures Against Various Sources of Variation can be Built into the Product

	Source of Variation		
Product Development Stages	Environmental Variables	Product Deterioration	Manufacturing Variations
Product design	O	O	O
Process design	X	X	O
Manufacturing	X	X	O

O- Countermeasures yes
X- Countermeasures no

The above table shows that countermeasures against performance variation caused by both environmental variables and product deterioration can be developed into the product during the product design phase.

It is not cheap to control a manufacturing process that is sensitive to manufacturing variations. Furthermore, the cost of detection and correction of manufacturing imperfections increases rapidly as the product gets nearer the end of the production line. Hence, countermeasures are best applied at the earliest possible stage in the design cycle when changes are less expensive to make. This is also stressed by Moen and Nolan (1987): the greatest benefits of improving quality would happen during the design of the product and of the manufacturing process. Many industrial statisticians feel that they can no longer concern themselves only with mean response, instead they must also consider the response variability in order to be cost effective (Vining and Schaub, 1996). Consequently, the use of robust design experiments to reduce variability has become an important goal in industrial experimentation.

3.4 Concept of Robust Design

"Robust" and "robustness" are terms widely used in automatic control: robustness is the property of a control algorithm to maintain stability in the presence of uncertainties or actual unknown disturbance present in the system (Sastry and Badson, 1989). That is output insensitivity to plant parameter variation, reasonable non-linear operation, modelling errors, and disturbances (Houpis and Lamont 1992). In the field of Statistics robust statistics or statistical methods are not sensitive to slight changes in their assumption (Staudte and Sheather 1990) and their results remain trustworthy even if a certain amount of data is contaminated or lost (Rouseeuw and Leroy 1987).

The key element of Taguchi philosophy is the concept of robustness in the design of products and/or processes. The concept of robust design was first introduced by Taguchi in the United States in the 1980's. In Taguchi's view, robustness means the ability of the design to express its intended performance during use with minimal variation. This criterion requires the design to be stable and consistent with the least sensitivity to all types of noise effects. Noise may include the effects of environment, degradation and age or operation conditions including human factor capability during operation and maintenance. According to Phadke (1989) "Robust design is an engineering methodology for improving productivity during research and development so that high-quality products can be produced quickly and at low cost." He further explained that often higher quality is associated with higher unit manufacturing cost. This was because engineers and managers, unaware of the robust design method, tend to achieve higher quality by using more costly parts, components, and manufacturing processes. The key idea behind robust design was illustrated by the experience of Ina Tile Company described in section 3.2. Yokohama and Taguchi (1972) have shown that the philosophy behind robust design was not limited to engineering applications, it has been applied in profit planning in business, cash-flow optimisation in banking and other areas. Robust design aims to make the product and process less sensitive to variations. That is, the product and process perform consistently well under all conditions. Both products and processes can be made robust. If products are robust with respect to variation in the quality of components and raw materials, then purchasing costs are reduced. Robust processes are insensitive to manufacturing variations and thus lead to less rework and scrap, and are also easier to control. Robustness to environmental conditions improves reliability and reduces operating costs because there are less breakdowns or periods of poor performance. Basically, Taguchi's approach to quality improvement was developed based on the work of W.A.Shewhart, L.H.C.Tippet, W.E. Deming, J.M. Juran and other pioneers (Bisgaard, 1993).

The basic issues addressed in robust design are how to reduce the variance of the product or process performance (response) either about some specified setting, or above, or below, some critical value. The fundamental principle of robust design, as pointed out by Phadke (1989) is "to improve the quality of a product by minimising the effect of causes of variation without eliminating the causes". That is, performance variation is reduced by reducing the influence of the sources of variation rather than controlling them. Robust design is also known as parameter design (Kacker, 1985; Tsui, 1988).

Taguchi (1986, 1987) in his approach to quality improvement, considered identifying settings of factors for the product and process as the most important stage in product development to achieve robustness against sources of variation. These factors which affect the product quality characteristics can be classified into two main categories: controllable factors and uncontrollable factors (noise). Control factors are those factors whose settings are within our control; we can adjust them comparatively cheaply and easily and once set to their optimum, the settings can be maintained in the future. Noise factors are those that are impossible or too expensive to control during actual production or use. They include environmental effects, manufacturing variations and deterioration over time. A product or process which consistently achieves its target performance in spite of these factors is described as being "robust against noise".

The concept of robust design in the context of manufacturing processes can be explained as follows: It is common practice, in the attempt to control variation in manufacturing, to make use of expensive and sophisticated control systems, and to tighten product and process tolerances. These increase the cost of production. However, there might be less need for such a control mechanism, if process parameter settings were selected so as to produce desired quality characteristics, regardless of manufacturing variations. Robustness with regard to sources of variation can also be achieved by appropriate selection of chemicals, procedures and equipment at the product design stage. If the desired results are searched again through such selections of product and process characteristics, it is not necessary to tighten tolerances of those characteristics.

Robust design of a process is a more effective and less costly way of reducing product variation (Kacker and Shoemaker, 1986) than 100% inspection at the end of manufacturing stage. Potentially, it can reduce the need for corrective procedures, thus reducing production lead time and cost. It also reduces the cost of controlling the sources of variation, and the need for on-line process control and inspection. The strategy of robust process design is first, settings of controllable process factors, which produce desired quality characteristics with minimum variation, are found. Then, a means of adjusting the average to target as necessary is developed. These steps are illustrated in figures 3.3(a) and (b).

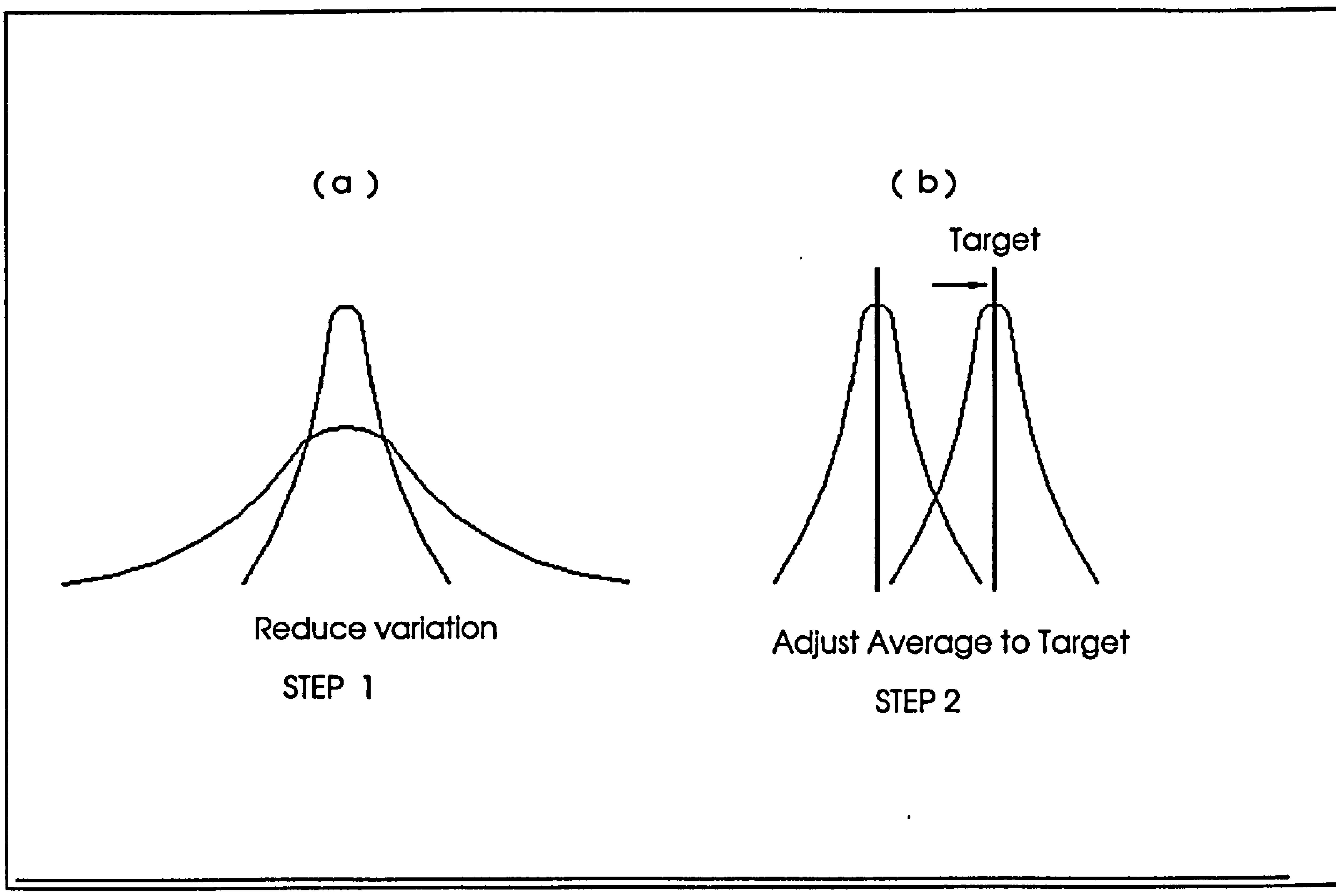


Figure 3.3 Robust Design Strategy

Robust process design is possible because the effects of sources of variation on process performance varies with the controllable process parameter settings. However, it is not always possible to achieve a desired level of robustness through selection of process parameter settings, because a combination of such parameter settings which will yield the desired level of sensitivity to the sources of variation may not exist.

Robust design relies heavily on experimentation to assess the effects of different factors on product or process performance. Steinberg and Bursztyn (1994) claimed that robust design experiments are especially effective when it is possible to build some variation directly into the experiment by including noise factors which are hard or expensive to control during production. The aim is to reduce variation in the process. The natural variation of these factors outside the experiment will introduce variability to product characteristics. Also, he added, when noise factors are introduced in a robust experiment, variation is built directly into the results which enables more efficient modelling of the process variation. Nevertheless Kacker (1985) highlighted that it was often not cost effective to introduce many noise factors in robust design, particularly in manufacturing process situations. This obviously would increase the number of runs, consequently increasing the cost.

3.5 Historical Development of Experimental Design

A "designed" experiment is a systematic method of changing the controllable factors (input) at different levels to observe their effects on some desired result (output) in the process. A factor is some feature that is believed to have an effect on the output or response. We may have two or more levels or settings for each factor that we could select for the experiment. Experimental designs are often utilised during the development phase and the early stages of manufacturing, rather than as a routine on-line or in-process control procedure. It is an upstream activity used for identifying improved factor levels in problems that involve a large number of factors. Hence, they are a series of techniques used to increase the efficiency of acquiring information about a process at minimum cost and time.

The experimental design method was originally invented by an English statistician R.A. Fisher in the 1920's. As part of this he introduced the idea of factorial experiments. A factorial experiment is defined as a structured method of changing multiple factors simultaneously to investigate their effect on one or more outputs in which combinations of factors (run) are allotted to one or more experimental units. In a full (complete) factorial experiment where every possible combination is run at least once, information about individual and joint effects of the factors on the mean response could be obtained. These are called "main effects" and "interaction effects", respectively. However, as the number of factors in a factorial experiment increases, the number of runs for a full replicate of the experiment rapidly exhausts the resources of most experimenters. For instance, to test eight factors each at two levels, a full factorial design would require $2^8=256$ runs. It is not possible, or practical, to run all combinations. Fortunately, Finney (1945) proposed the use of fractional factorial experiments in such situations. These designs contain a fraction of the runs in the complete factorial experiment, allowing the estimation of all main effects and often lower order interactions under the assumption of zero higher order interactions. That is, a fractional experiment is a subset of the full set of combinations from a full factorial experiment. Information on higher order interactions is discarded to accommodate extra factors or to reduce the number of testing runs, for example a screening experiment. However, this can lead to difficulties which could distort our view of the main effects. Then, in the late 1940's, Galois field theory was found to be useful in the construction of fractional factorial experiments which gave orthogonal estimates of the factorial effect. Bose (1947) presented the general theory of symmetric factorial experiments, leading Rao (1947) to further improve upon and to propose the use of orthogonal arrays in factorial designs. Experimental designs were initially applied in agricultural experiments. It was then introduced to the manufacturing industries, initially the chemical industry, after the statistical designed experiments had been further developed by statisticians such as Cochran and Cox (1957). See also the publications of Hicks (1973), Daniel (1976), Box et al. (1978) and Kempthorne (1979).

In fractional factorial experiments, "Plans" which permit estimates of all main effects when all interaction effects are zero are called Resolution III plans. The expression "Resolution R plan " was originated by Box and Hunter (1961). In the case where very few known lower-order interactions are non-zero, using search designs are quite useful. Srivastava (1975) proposed the theory of search designs that allows estimates of lower-order interaction effects, and the searching of non-zero higher-order interaction effects. This method permits inference about those non zero higher-order interaction effects as well as on lower-order interaction effects.

With so many confounding patterns, it is helpful to have a way to classify the "degree of confounding". The term Resolution (R) describes the confounding with a number that signifies the number of factors that are tied together (confounded). A higher resolution number indicates less confounding. Basically there are four confounding patterns as listed below:-

(1) A resolution III design has main effects mixed or aliased with two-factor interactions. In this design the main effects are not mixed with any other main effects.

(2) A resolution IV design has at least one two-factor interaction mixed with other two factor interactions, but does not have any main effects mixed with each other or with two factor interactions. However two factor interactions are mixed with two-factor interactions.

(3) A resolution V design does not have any main effects or two-factor interaction effects mixed with each other, but some two-factor interactions are mixed with three factor interactions.

According to Lochner and Matar (1990), resolution IV designs are used more often because they seem to provide a good balance of useful information versus the number of trials required. For a small trial experiment, resolution III designs give a lot of information but can be misleading if there are too many confounding of factors. Resolution V designs are probably too costly for many situations. The designing of experiments is a crucial part of robust design activities (Phadke, 1989; Ross, 1988; Phadke et al. 1983; Taguchi, 1987; Taguchi et al. 1989; Welch et al. 1990; Logothetis and Wynn 1989). This is achieved by using fundamental principles of statistical experimental design theories, such as randomisation, replication and blocking (Box et al., 1978; Box and Draper 1986).

Designed experiments have been applied to improve industrial processes for more than 60 years but its application in product design improvement only begun in the late 1970's. After Taguchi has advocated the use of statistical designed experiment methods for product design improvement. However, most applications optimise the mean value of a response variable. Kacker (1985) reported that in industrial processes, it is often much easier to control the mean value than controlling the variation, and variation can be a root cause of high manufacturing costs.

3.6 Criticisms on Taguchi's Approach

Khattree (1996) claimed that as far as Taguchi's philosophy of quality engineering is concerned, it is very sound . He further reported that there was "little disagreement" among the researchers and practitioners about his basic philosophy. On the other hand, Lochner and Matar (1990) and Kacker et al. (1991) stated that Taguchi's approach to experimental design is similar to the classical statistical approach. The orthogonal standard design matrices proposed by Taguchi were based on Fisher's idea, except that they are presented in a different arrangement to that of the standard Yates order (Box et al., 1988). Lochner and Matar (1990) and Kacker et al. (1991) reported that they can be converted to the classical statistical format with some arrangement. Although Taguchi's concepts provide a powerful tool for improving product and process design, the efficiency of his statistical techniques has been challenged (Box, 1988; Box et al., 1988; Leon, et al., 1987; Ryan, 1988; Bisgaard, 1993; Bendell et al., 1990).

While there is much debate about the appropriateness of Taguchi's strategies, his methods of data analysis and approach have received considerable attention by practitioners (Kacker, 1985; Pignatiello and Ramberg 1985; Tjantele', 1991; Nair and Pregibon, 1986; Nair and Shoemaker 1990). Wu (1992) also added that Taguchi's work is widely acknowledged. Before Taguchi's concept became known, (Lucas, 1992) the statistical design of experiments was seldom used by engineers, but after he had demonstrated their practical power, engineers started to use them more widely. However he added that in many instances Taguchi has not proposed "quite the proper analysis" and suggested the merging of the positive aspects of Taguchi's proposals with the classical experimental design and analysis. According to Myers et al. (1992) Taguchi concepts have been overshadowed by controversy related to his approach to modelling and data analysis. Nevertheless some of Taguchi's critics have also pointed out the positive aspects of robust design in the field of quality engineering, both with and without the use of analytical methods introduced by Taguchi. Many applications of Taguchi methods have been reported in areas such as the automotive, plastic and electronic industries.

Phadke (1992) argued that "the lack of adequate literature in the English language, the evolving nature of the methodology, and the lack of understanding of the engineering issues on the part of statisticians have been responsible in part for the misunderstanding and debate". The most debated aspects of Taguchi's approach to robust design are Signal to Noise (S/N) ratios, the use of inner and outer arrays (also known as cross product/array design) and interactions.

Taguchi's Signal to Noise (S/N) ratios are sometimes misleading and can lead to wrong decisions (Nelder, 1992). Information on dispersion and location effects are confounded with each other and all of the information in the data is not used. S/N ratios are ineffective in identifying dispersion effects (Hamada, 1993), although they serve to identify location effects (Montgomery 1991). Modelling the mean and the variance separately through response surface methods (Hare 1990, Vining and Myers 1990; Myers et al., 1992; Nelder and Lee 1991, Buck and Wynn 1993) is more effective and can provide information on the dispersion effect. Nelder and Lee (1991) highlighted that data transformation to improve its statistical properties, explanation and prediction were not well addressed in Taguchi's approach. Box (1993) suggested a better alternative to S/N ratios was to use the log transformation to decouple the dispersion and location effects and so simplify finding those conditions that simultaneously locate the process on target and reduce dispersion about the target.

The use of the outer arrays for the noise factors for every experimental run that belongs to the inner array leads to a large number of experimental runs (Shoemaker et al., 1991; Buck and Wynn 1993). As pointed out by Box (1985), there are superior methods available in classical design theory, which can be employed to handle both controllable and noise factors. A better strategy could be to assign the controllable and noise factors to a single design array also called combined array (Shoemaker et al. 1991; Box and Jones 1992). The basic idea was proposed by Welch et al. (1990). This approach is simpler, more efficient and will need fewer experimental runs. Shoemaker et al. (1991) investigated the reasons for the substantial reductions in the experimental runs. They found that the product array design was configured in such a way that the effects consist of all generalised interactions between the estimable effects in the control array and the estimable effects in the noise array. In reality, many of these effects would be insignificant. In contrast, the combined array permits flexibility in the choice of predicted effects. This estimation flexibility leads to savings in run size. Shoemaker et al. (1991) also added that using information in hand and leaving out some effects, one could select a combined array with a significantly reduced run size. Another important aspect of this approach is the possibility of allowing sequential experimentation which is often not possible when using the inner and outer array.

Lorenzen and Villalobos (1990) made a comparison study of the different approaches to the design and analysis of robust design experiments. They noted that modelling the raw data appears to be the best possible approach for analysing data from a robust design experiment. This is followed by separately modelling the mean and log-standard deviation. Modelling the loss function directly will be the worst procedure. They concluded that the combined array also known as the single experimental array design is "superior for robustness" because their assumptions can be checked. Sacks and Welch (1992) further claimed that their investigation using the response methodology showed that: first, the single experimental array for both control and noise factors will usually require far fewer observations than Taguchi's crossed/product arrays, even when interactions between the control factors are included. Secondly, engineers are more likely to have background knowledge when modelling the quality characteristic of interest than when modelling S/N ratios. Related to this, the response model provides a better picture of how the factors affect the quality characteristic. They found that the quality characteristic is often easier to model than S/N ratio. Wahid and Metcalfe (1996) conducted a study on spot welding using inner and outer arrays design and analysed the results using both S/N and regression techniques. They reported that both techniques have showed quite similar conclusions. The only drawback about the regression approach is that it requires some subjective application of the statistical technique and cannot easily be described as a set procedure. It also depends completely on how well the model fits. For instance, if we omit from the model a noise factor that has large interaction with a control factor, the combined- array experiment may lead to control-factor settings that actually increase variability. Shoemaker et al. (1991) suggested that confirmation experiments and model diagnostics are ways to avoid model "misspecification" in combined-array experiments. Model selection and checking techniques such as stepwise regression and normal score plots of residuals can also be used (Box et al.1978; Daniel 1976). However, Kacker (1992) argued that missing data and other disturbing outcomes usually occur in experimentation, and the combined-regression approach is sensitive to missing data. Despite missing data, inner and outer array designs can usually provide information for further study.

Next, interactions are normally not considered in Taguchi's approach (Easterling, 1985), particularly at the initial stage of the experiment. Even though in the "real world" two factor interactions have a high probability of existing, Taguchi normally considers only main effects. This is because of Taguchi's view that in most industrial engineering problems, the primary objective is to test for main effects because there are many factors to investigate. Also, to facilitate testing for a large number of factors, interactions are assumed to be known in advance before the experiment. Freund (1985) argued that even though good results are obtained from Taguchi's approach, it is nevertheless important to learn which way interactions contribute. Hence it becomes important to be able to determine which interactions occur so that the underlying cause can be better understood. Moreover, the approach is not based on a learning process, and so process knowledge which can be useful in future problem is not acquired.

Other disadvantages of Taguchi approach according to Box (1992) and Bisgaard (1993), are that the experimental strategy seems to rely on one large comprehensive experiment or "one-shot approach". They disagreed with this approach because it was not an iterative learning process involving a sequence of experiments which is not wise and economic. Several approaches have been proposed for optimising both the mean and variation of a process simultaneously.

There has been considerable research aimed at integrating robust design principles with sound statistical techniques. For example, Bullington et al. (1993) conducted a comprehensive case study on an industrial thermostat using Taguchi's method. They combined the methods with appropriate statistical analysis and concluded that this application yielded a product that has higher reliability and shorter production cycle times. The new robust process attained through this investigation allow the company to penetrate new markets due to their ability to function in a severe environment.

In an Integrated circuit manufacturing example, (Shoemaker et al. 1991) showed how examination of control-by-noise interaction plots revealed the mechanism by which two control factors dampened the effects of two noise factors.

Pereira and Aspinwall (1993) applied robust design in the food industry. In their application they considered the role of a few interactions and the need for transforming the data which are normally neglected in Taguchi's experiments. They concluded that Taguchi's method should be integrated with well established statistical methods so that technical staff who have little statistical knowledge could easily understand and implement them.

It is obvious that to benefit from Taguchi's idea of robustness and classical statistical methods, we should integrate the merits of both. This study will adopt this approach in order to seek continuous quality improvement for the rubber glove industry.

3.7 Chapter Summary

This chapter discussed the evolution of quality improvement procedures and the strategies that have been employed to gain industrial competitiveness. We argue for the need to shift emphasis to the upstream side rather than downstream side of the process as changes could be made at lower cost. We also discussed about product performance variability. Next, we discussed countermeasures that could be taken in order to prevent the occurrence of poor quality product. We then introduced the concept of robustness in terms of variation to keep the cost of manufacturing down but at the same time, maintain a high quality product. We later discuss criticisms of Taguchi's approach to design experiments for product and process improvements. In the next chapter, we will discuss how to design an experiment in the context of rubber glove manufacturing, integrating both the concept of robustness and the classical statistical methods, in order to improve the production process.

CHAPTER 4

ROBUST PROCESS DESIGN

4.1 Introduction

Robust process design in general has been reviewed briefly in section 3.3. This chapter, describes the application of robust process design to a rubber glove manufacturing process. The problem of the design of a robust process for making rubber gloves is defined in terms of objectives, controllable and uncontrollable (noise) factors. The problem environment is also introduced as a specific case which is used to demonstrate the design methodology.

Rubber glove manufacturing processes are required to make products with the desired quality characteristics specified by customers, consistently within and among batches (lots) and at low cost. Achievement of this goal is made more difficult by the presence of multi factors in the environment, such as variation in the dust particles, water quality, chemicals, humidity and manufacturing process conditions. Elimination of such variations is usually either expensive or impossible altogether. However, it may be possible to minimise the sensitivity of the glove process to such manufacturing variations just by careful selection of the process settings.

Therefore, what we meant by the design of a robust process for making rubber gloves are :-

1. Making the process less sensitive to environmental factors or other factors that are difficult to control. That is to minimise the effect due to variation which results from environmental sources such as humidity, vibration etc.

2. Reducing process variability around the target value. This means that deviation around the mean response is minimised.

Although achieving robustness at product design is vital, in this study, the focus is on the robustness of process design. The experiments are performed in the production environment or "real world".

Before we can plan the tests that will be incorporated into our experiment, we have to decide on what we are looking for in a systematic and controlled manner. Experimental costs and analysis costs are two important criteria to be considered at the planning phase. We will discuss fractional factorial designs in order to address the issue of cost.

The problems encountered in fractional factorial experiments will be discussed. Since only a fraction of the experiment is run, confounding inevitably takes place. That is, the estimated effects will be distorted by effects of other factors.

4.2 Experimental Strategy and Planning

Planning an experiment is crucial to the success of a project. The concept of PDSA (Plan Do Study Act) was adopted in solving the problem. During the planning phase we identified a project team which comprised a representative from each of the technical and production departments together with the author. This team identified four responses of interest to be studied because these responses are the customers' need. Five two-factor interactions of interest were also identified based on the process knowledge and experience of the Production and Quality Executives. The scope of the experiment to be covered was determined. That is the rubber glove dipping process, starting from the cleaning of the formers to the stripping of the gloves as previously discussed in chapter 2. During this stage, we also took into account prior knowledge of the process. For example, some combination of factors (conditions) might be known to give poor results or might not be attainable with existing machines or equipment. Hence the outcome of certain experimental conditions could be expected.

We then formed a different group for brainstorming which was comprised of the operating personnel and the Technical Executive. In the brainstorming session the members of the group were encouraged to suggest as many as possible the causes on the effect (problem). These causes were arranged into a Cause-and-Effect diagram as presented in Figure 4.1. This diagram resembles the skeleton of a fish, and it is often referred to as a "fishbone" chart. The fish head is the effect and the large bones indicate the major categories of potential causes, while the small bones carry the minor categories. The causes that influence the result of the output are classified into man, machine, material, environment, measurement and method.

The purpose of this chart is to facilitate focused brainstorming, argument, and discussion among members regarding what might be the cause of the problems or defects. Sometimes, some of these causes could be discarded by simply talking them over. This technique would give some clues to the problem solving. Nevertheless some of these causes would be left unknown. Thus utilising the information gathered from the industrial process often helps sort out the different possibilities. The brainstorming session also helps to develop team spirit and attitude and assure maximum participation by the group members. This would make the execution of the experiments slightly easier, since some of the operating personnel would be working on the production line chosen for running the experiments.

After the brainstorming, the project team defined the objectives and scope of the experiments as well as scheduled trial runs to be conducted. As listed below, the objectives are:-

(1) To determine factor levels which reduce process variability and which give the best setting conditions.

(2) To identify factors affecting the mean and variability of the responses.

(3) To establish relationships between input and output variables through a statistical model.

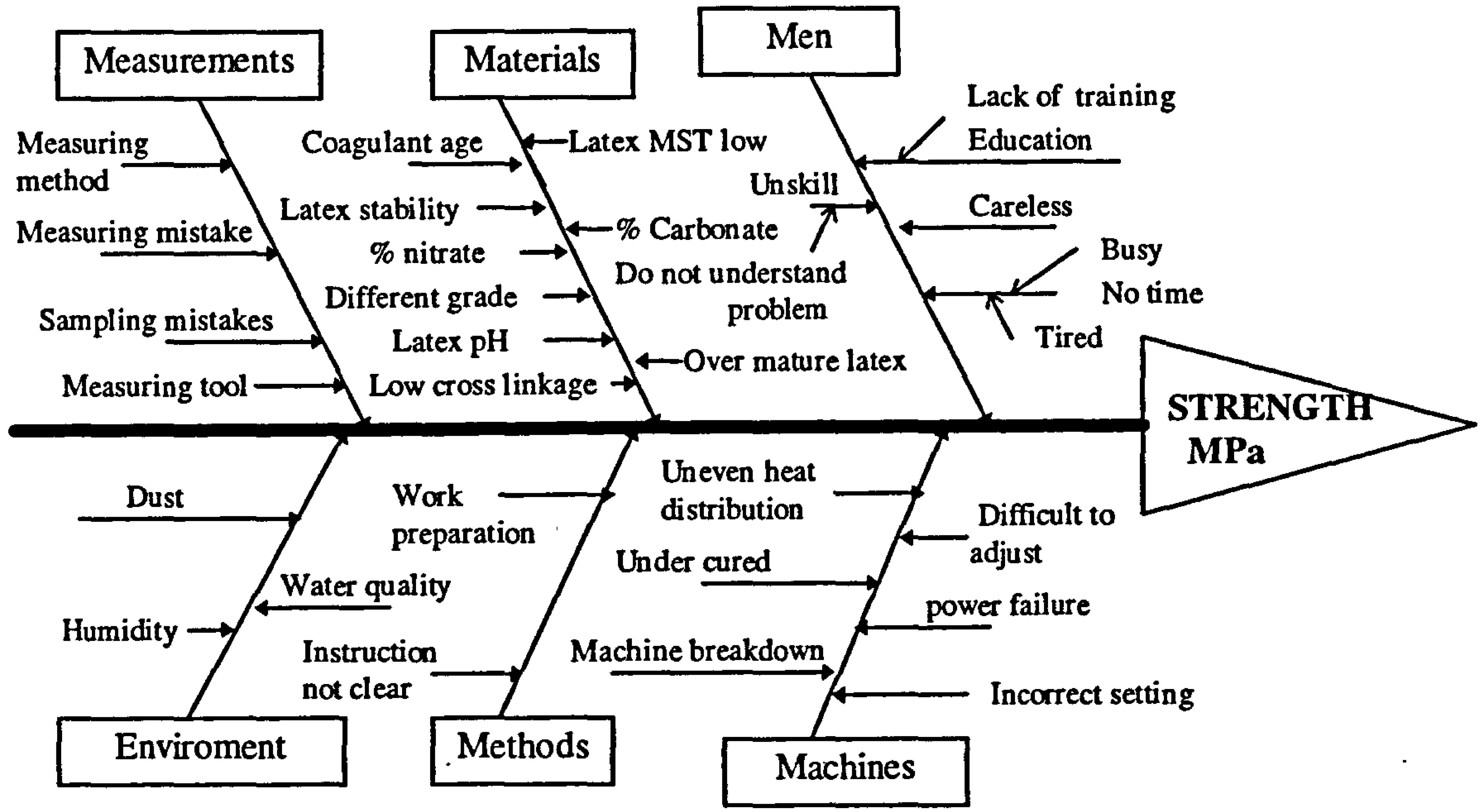


Figure 4.1(a) Cause and Effect Diagram for Variation in Tensile Strength

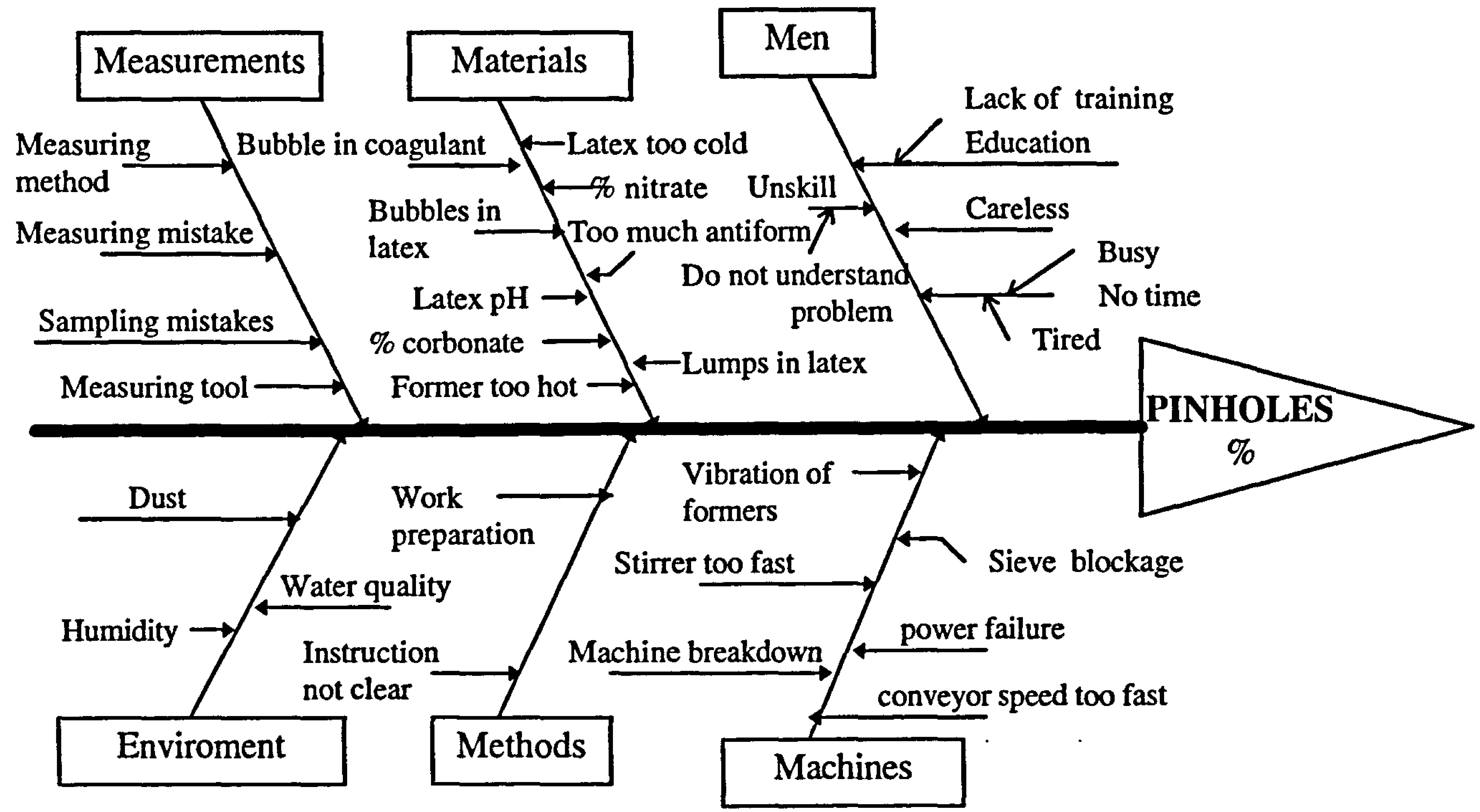


Figure 4.1(b) Cause and Effect Diagram for Variation in Pinholes

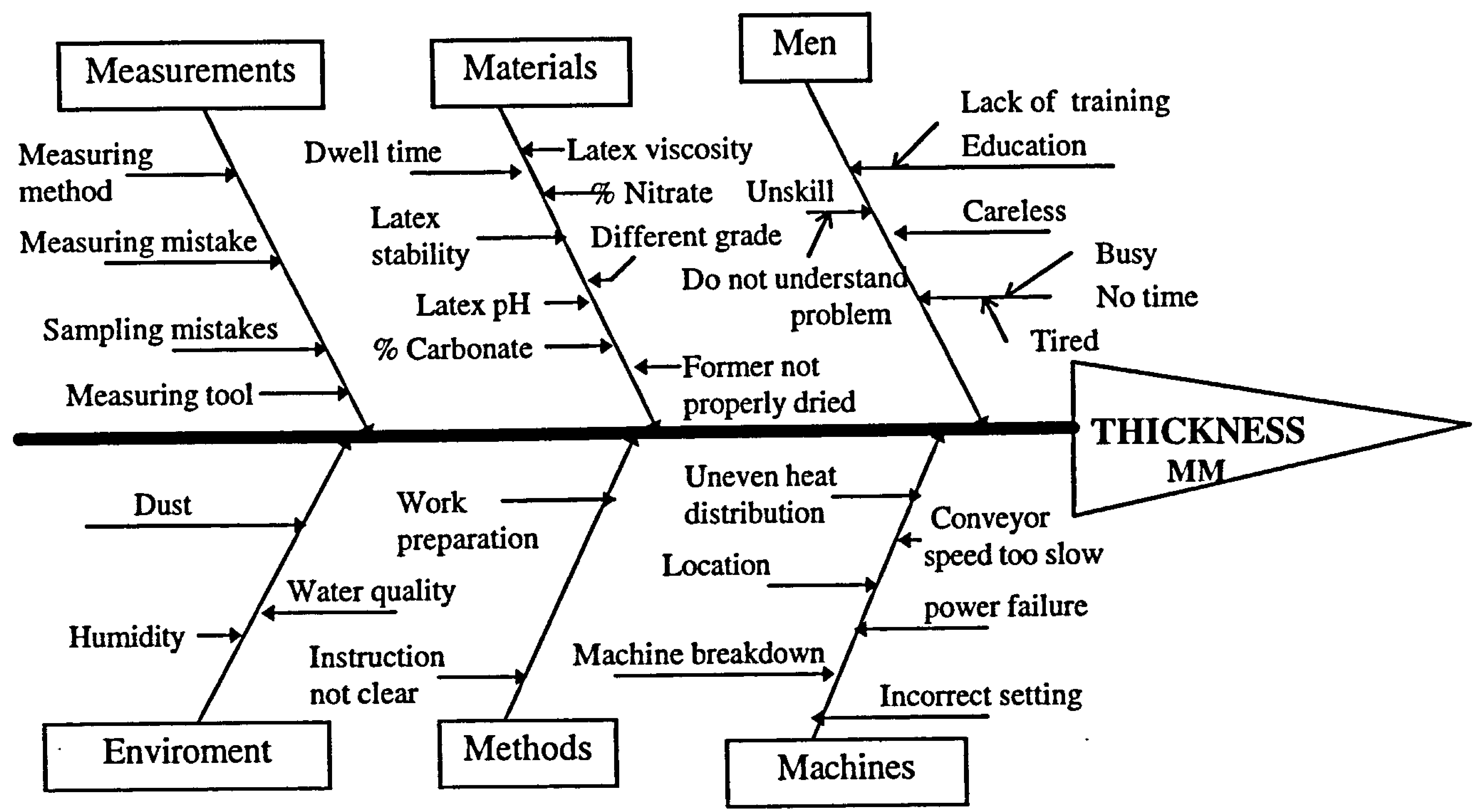


Figure 4.1(c) Cause and Effect Diagram for Varaition in Finger Thickness

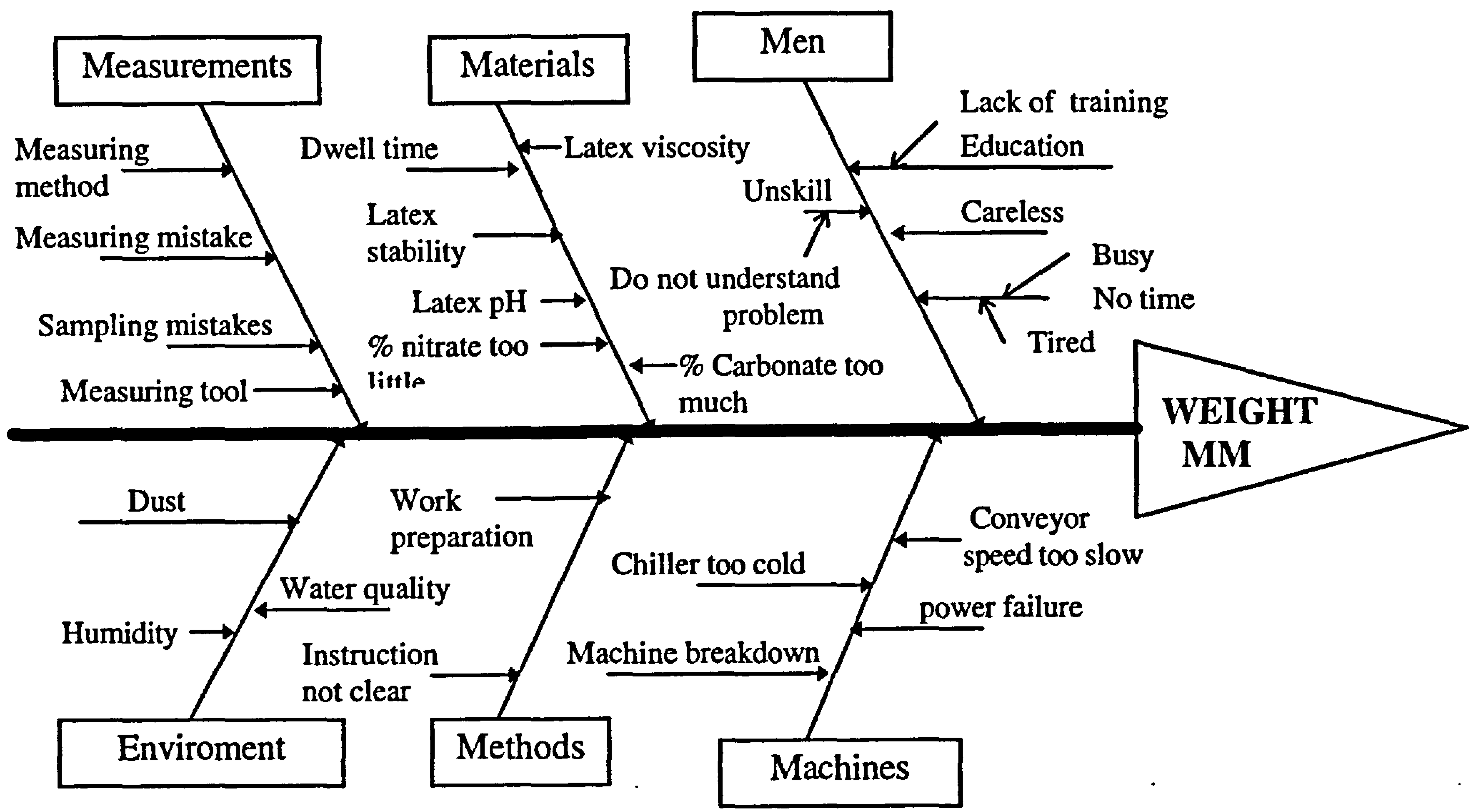


Figure 4.1 (d) Cause and Effect Diagram For Variation in Weight

4.3 Factors Affecting Process Outcome

The outcome of the process may be affected by several factors such as materials, equipment, machine controls, procedures, schedules, operators and utilities. Most of them are possible causes of defective products. Some of these factors can be adjusted to alter the response of the process. These are factors associated with the process whose level can be set by the process operator (designer). They are called "controllable factors" by Taguchi and "design parameters" by Kacker (1985). For instance, the quality characteristics of rubber gloves are sensitive to the stability of latex and chemical selection. The outcome could be affected by choosing a different dipping technique or following a different formulation. Similarly, by changing the settings of process parameters such as curing temperature and conveyor speed, it is possible to improve the output. In fact, the main focus of this study is finding the process settings which would produce the best output regardless of the settings of the other factors.

Many of the factors affecting the outcome are difficult, expensive or impossible to control. These factors cause random changes in the glove making process, and are referred to as uncontrollable factors or noise factors. Some significant noise factors are variations in the dust particles, humidity, water quality and variation in manufacturing. Other noise factors which are not included in the experiments are; for example, variations in the age of formers, full line operation, time of antifoam addition into the dipping tanks and age of the coagulant in the dipping tanks. These variations, therefore, are not studied. These variations are already well understood and rather easy to detect and rectify. The age of formers could be identified through its colours. Once they turn yellow, it is time to change them. If they are not changed, they could impart yellowish colour to the gloves. Similarly, the age of the coagulant in the dipping tanks could be detected easily: if microbial counts are low, the coagulant could still be used. All these factors are being monitored regularly.

Finally, there are also some factors which do not affect the glove itself, but have impact on measurements of the product. These are errors in preparation and presentation of samples for quality characteristics measurements. For example, the weighing scale, tensile machine, thickness gauge etc., are equipment used to measure the dimensions of the gloves. If these are not calibrated or set properly, they could affect the results of the experiments. Minimisation of these errors is crucial for a successful design of the process.

Randomisation and blocking procedures are some of the basic ways to overcome these effects and will be discussed in section 4.6.

4.4 Selection of Control and Response Variables

The initial step in setting up the experiment is to choose the factors which will be included in the experiments. Some, but not necessarily all, of the controllable factors will be chosen. Certain controllable factors may be fixed for reasons of economics, because their effects on quality characteristics of interest are already well understood, or because they are required to be fixed at certain levels due to their effects on other quality characteristics.

After brainstorming, seven controllable factors and two noise factors were selected for the robust process design. The controllable factors were curing temperature profile, temperature of latex in dip tank, oven temperature before coagulant dip (formers' temperature), percent calcium nitrate, percent calcium carbonate, oven temperature before latex dip and pH of latex compound. The factors and their levels are listed in Table 4.1. Three of these factors are easily controllable; oven temperature before coagulant dip (formers' temperature), curing temperature profile and pH of latex compound. While the other three variables are not easily controllable during routine manufacturing; percent calcium nitrate, percent calcium carbonate and pH of latex compound. The practical constraints in performing the experiment would be the changing of the chemicals concentrations which is very labour intensive. By contrast, changing the latex temperature would be very easy, but it is time consuming to raise the temperature.

As stated earlier, one of our main objectives is to determine which of the eight factors have a strong influence on the process output. Hence, we may screen out factors that were not thought to have a big effect on the process output. Therefore, it is best to keep the number of factor levels low. Furthermore, we are at early stages of the experimentation. For these reasons we chose two levels for each factor in the experiment

With a large number of noise factors, an experiment can become quite expensive. By carefully selecting noise factors we can keep the size of the experiment within manageable limits. In this regard two noise factors were considered because they were thought to have the strongest effect on the quality characteristics of interest. These noise factors were humidity and dust particles. We later discovered that it was difficult to monitor dust particles in the environment because the company did not have the facilities and personnel to measure the dust particles. Consequently this option was not chosen. The relative humidity was identified because its inclusion in the experiment did not involve any cost, and it was quite easy to implement. Often it is difficult to build in noise which can be controlled. In our case this was true. We could not control relative humidity during the experiment. In this circumstances we made use of the behaviour of relative humidity. That is, the relative humidity in constant temperature ovens is low at night and high in the day. By this way, the uncontrollable noise factor is going to make its presence felt continuously during the experiment. The two-levels were established for the relative humidity.

The response variables of interest (quality characteristics) identified to be estimated are pinholes, strength, finger thickness and weight. The first three responses play an essential role in satisfying users' needs. For instance, with a glove for surgical purposes, it is crucial that it contains no pinholes. Otherwise, viruses could be easily transferred through these holes and the outcome could be disastrous for either patient or doctor. Similarly, the strength of the gloves has an important role to play. If a glove bursts or tears when a surgeon puts it on, this could lead to work being delayed. This could even be more serious if the glove tears while an operation is on. It could affect a patient's life. The glove's thickness can affect the sensitivity of the "feel" when in contact with an object during an operation. Some surgeons want the glove to be thin and some want it vice-verse. As regards to the weight, it is more for internal use to monitor the number of gloves per carton during packing.

Factors can affect a response variable in two ways; by changing the average value or by changing the amount of variability. To analyse for changes in variability, it is necessary to estimate the amount of variability at each "point" in the experimental design. In this case, we need to obtain repeat observations for each combination of factors used in the experiment. For an example, in every trial run we took a sample size of ten for the thickness measurements, sample size of 3 for the tensile strength, sample size of 10 for the weight and sample size of 100 for pinholes. The experiments were replicated under the same conditions and another set of samples were taken for each run. The standard deviation of the response at each experimental point was calculated for replicate one and two and the standard deviation between these replicates was estimated for the variability.

Table 4.1 Factors and Levels for Rubber Glove Experiment

Factors	Level	
	Low (1)	High (2)
Curing temperature profile (A)	80 100 115 115 120 130 °C	95 110 125 125 130 150 °C
Temperature of latex in dip Tank (B)	25-26 °C	29-30 °C
Oven temperature before coagulant dip (C)	75-80 °C	90-95 °C
Calcium nitrate (D)	7.0-8.0 %	11.0-12.0 %
Humidity (E)	Low	High
Calcium Carbonate (F)	2.5-3.5 %	4.5-5.5 %
Oven temperature before latex dip (G)	170-180 °C	190-200 °C
pH of latex compound	10.1-10.5	10.6-10.9

4.5 Construction of Design Layout

To determine the effects of different levels of the control factors on the glove manufacturing process when it is subject to random noise, it is more efficient to perform experiments according to a factorial design. This type of design or layout requires a smaller number of trials than a full factorial experiment and still provides estimates of some of the interaction effects in the experiment. However it depends on the fraction used. Hence, the running of the experiment would no longer be economical. Experimental cost and analysis cost are two important criteria to be considered in approaching the design layout for the rubber glove process.

In our case study, we have seven controllable factors and one noise factor where each factor is set at two different levels. The design experiment will be 2^{8-4} fractional factorial design. The factor levels are fixed. Both controlled and noise factors affecting the process outcome were combined in a single experimental setup, also called a combined array (Shoemaker et al. 1991; Welch et al.1990). This combination array approach allows us to design experiments more economically and to estimate only selected effects. The appropriate orthogonal array to be used for the experimental design is L16 array. This means there are 16 trial runs in the experiment instead of 256 required by a full factorial experiment. The process conditions shown in Table 4.1 are used to set-up the experiment and the runs to be made are shown in Table 4.2.

The design layout refers to the combinations of setting for the experiment factors which are included in the experiment and can be summarised by a design array. The experimental design is based on various levels of these control factors. We then assign the main factors (A, B, C, E, D, F, G, H) to columns 1, 2, 4, 7, 8, 11, 13 and 14 as in Table 4.4. Other control factors which are well known and easily rectified as discussed in section 4.3 and 4.4 or outside the scope of this work are held constant during the experimentation. According to statistical experimental design terminology, the control and noise factors listed in Table 4.1 are independent variables which can be set to any value within a specific region during the experiment.

A sixteen-runs two-level fractional factorial experiment for varying eight factors simultaneously is summarised in Tables 4.3 and 4.4. Each column of the design array corresponds to a particular experimental factor and each row in the table represents a combination of factor settings or run included in the experiment. A minus sign (−1) in a column means that the factor listed above the column should be adjusted at its low level. A plus sign (+1) indicates that the factor should be adjusted at its high level in that particular run. According to Table 4.3 the first trial run would be with all factors set at low levels. In the second trial run, factors A, E, F and G would be set at their high levels and factor B, C, D and H at their low levels. The order in which these 16 trial runs were performed were randomised completely so as to reduce the effects of factors which are not controlled in the experimentation. A random number from the hand calculator was generated and allocate each trial run a number and order them through random numbers. As illustrated in Table 4.3 the standard run 12 was performed first, followed by 6, 1, 15 etc. The randomisation procedure dictates the running order of the experiments. This running order of the experiments is used to set-up the experiment as shown in Table 4.2. For the actual (randomised) run 12 curing temperature profile (A), latex temperature (B), and percent calcium nitrate (D) and percent calcium carbonate (F) would be set high and

Formers' oven temperature (C) humidity (H), oven temperature before latex dip (G) and pH of latex (H) should be at low.

Table 4.2 Experimental Set-up

Std run	Actual run	Curing temperature profile	Temp of latex	Former oven temp	Humidity	Calcium nitrate	Calcium carbonate	Oven temp after coagulant dip	Latex pH
		°C	°C	°C	%	%	%	°C	
1	12	95 110 125 125 130 150	29-30	75-80	Low	11-12	4.5-5.5	170-180	10.0-10.4
2	6	95 110 125 125 130 150	25-26	90-95	Low	7-8	4.5-5.5	170-180	10.5-10.7
3	1	80 100 115 115 120 130	25-26	75-80	Low	7-8	2.5-3.5	170-180	10.0-10.4
4	15	80 100 115 115 120 130	29-30	90-95	Low	11-12	2.5-3.5	170-180	10.5-10.7
5	3	80 100 115 115 120 130	29-30	75-80	High	7-8	4.5-5.5	170-180	10.5-10.7
6	11	80 100 115 115 120 130	29-30	75-80	High	11-12	2.5-3.5	190-200	10.0-10.4
7	10	95 110 125 125 130 150	25-26	75-80	High	11-12	2.5-3.5	170-180	10.5-10.7
8	13	80 100 115 115 120 130	25-26	90-95	High	11-12	4.5-5.5	170-180	10.0-10.4
9	16	95 110 125 125 130 150	29-30	90-95	High	11-12	4.5-5.5	190-200	10.5-10.7
10	2	95 110 125 125 130 150	25-26	75-80	High	7-8	4.5-5.5	190-200	10.0-10.4
11	8	95 110 125 125 130 150	29-30	90-95	High	7-8	2.5-3.5	170-180	10.0-10.4
12	14	95 110 125 125 130 150	25-26	90-95	Low	11-12	2.5-3.5	190-200	10.0-10.4
13	7	80 100 115 115 120 130	29-30	90-95	Low	7-8	4.5-5.5	190-200	10.0-10.4
14	5	80 100 115 115 120 130	25-26	90-95	High	7-8	2.5-3.5	190-200	10.5-10.7
15	4	95 110 125 125 130 150	29-30	75-80	Low	7-8	2.5-3.5	190-200	10.5-10.7
16	9	80 100 115 115 120 130	25-26	75-80	Low	11-12	4.5-5.5	190-200	10.5-10.7

Note: Std run = standard run, Temp = Temperature

Table 4.3 L16 Orthogonal Array with Main Factors

Std run	Actual run	A	B	C	E	D	F	G	H
1	12	–	–	–	–	–	–	–	–
2	6	+	–	–	+	–	+	+	–
3	1	–	+	–	+	–	+	–	+
4	15	+	+	–	–	–	–	+	+
5	3	–	–	+	+	–	–	+	+
6	11	+	–	+	–	–	+	–	+
7	10	–	+	+	–	–	+	+	–
8	13	+	+	+	+	–	–	–	–
9	16	–	–	–	–	+	+	+	+
10	2	+	–	–	+	+	–	–	+
11	8	–	+	–	+	+	–	+	–
12	14	+	+	–	–	+	+	–	–
13	7	–	–	+	+	+	+	–	–
14	5	+	–	+	–	+	–	+	–
15	4	–	+	+	–	+	–	–	+
16	9	+	+	+	+	+	+	+	+

Note: A = curing temperature profile, B = temperature of latex in dip tank, C =oven temperature before coagulant dip, D = calcium nitrate %, E = humidity, F = calcium carbonate, G = oven temperature before latex dip H = pH of latex compound. Std= Standard

Table 4.4 L16 Design with Interaction Columns

	Columns														
	A	B		C		AE	E	D	BF	BD	F	CD	G	H	BG
Trial	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
1	–	–	+	–	+	+	–	–	+	+	–	+	–	–	+
2	+	–	–	–	–	+	+	–	–	+	+	+	+	–	–
3	–	+	–	–	+	–	+	–	+	–	+	+	–	+	–
4	+	+	+	–	–	–	–	–	–	–	–	+	+	+	+
5	–	–	+	+	–	–	+	–	+	+	–	–	+	+	–
6	+	–	–	+	+	–	–	–	–	+	+	–	–	+	+
7	–	+	–	+	–	+	–	–	+	–	+	–	+	–	+
8	+	+	+	+	+	+	+	–	–	–	–	–	–	–	–
9	–	–	+	–	+	+	–	+	+	+	+	–	+	+	–
10	+	–	–	–	–	+	+	+	–	+	–	–	–	+	+
11	–	+	–	–	+	–	+	+	+	–	–	–	+	–	+
12	+	+	+	–	–	–	–	+	–	–	+	–	–	–	–
13	–	–	+	+	–	–	+	+	+	+	+	+	–	–	+
14	+	–	–	+	+	–	–	+	–	+	–	+	+	–	–
15	–	+	–	+	–	+	–	+	+	–	–	+	–	+	–
16	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+

Note: Columns 1-2, 4, 7-8, 11, 13 and 14 represent the main factors. Columns 3, 5, 6, 9, 10, 12 and 15 represent the two-factors interactions. A minus sign (–1) indicates that the factor should be set at its low level and a plus sign (+1) indicates it should be set at its high level.

The experimental design illustrated in Tables 4.3 and 4.4 has the property of being orthogonal. The orthogonality property means that for every pair of columns, each possible combination of levels appears, and appears the same number of times. Therefore a comparison of factor levels effects on the response could be evaluated. An orthogonal array is made up of columns and rows. The number of columns of an array represent the maximum number of factors and interactions that can be studied. The number of rows of an orthogonal array represents the number of experiments. Most of these arrays are found in Bartlett and Kendall (1946), Plackett and Burman (1946), who invented these designs and the work of Addelman (1962, 1962a, 1972), Box and Hunter (1961). This property is essential because it allows estimation of the average effects of factors without worrying about the results being distorted by effects from other factors. To determine orthogonality, first multiply the row values from each of two columns. For instance, column A multiplies column B as illustrated in Table 4.5. When any two columns are multiplied together, there will be an equal number of + signs and – signs in the resulting column. The product of column C×G has equal number of + and –. The use of orthogonal arrays ensures that each column provides a separate estimate of various factors. Thus, the effect of each factor can be evaluated independently of all other factors. The columns of an orthogonal array are called orthogonal contrasts.

Table 4.5 Orthogonality

Column C	Column G	Column C×G
+	–	–
–	+	–
+	+	–
+	–	–
+	+	+
–	–	+
–	–	+
-	+	+

Finally, these products are summed. If the sum is equal to zero, the columns are orthogonal and the effects represented by these columns are also said to be orthogonal.

$$\begin{aligned}\text{Sum} = {} & (-1)(-1) + (1)(-1) + (-1)(1) + (1)(1) + (-1)(-1) + (1)(-1) + (-1)(1) + (1) \\ & (1) + (-1)(-1) + (1)(-1) + (-1)(1) + (1)(1) + (-1)(-1) + (1)(-1) + (-1)(1) + (1)(1) \\ = {} & 1-1-1+1+1-1-1+1+1-1-1+1+1-1-1+1 \\ = {} & 0.\end{aligned}$$

The effect of a factor on a response variable is the change in the response when the factor varies from its low level to its high level and vice versa. The effect of any factor on the response will not be distorted by the effects of other factors, since the design is orthogonal. An experiment design, which has incorporated the use of orthogonal tables, is called an orthogonal experimental design.

An orthogonal array is a factorial design basically used for estimating main factor effects. The construction of orthogonal arrays is important in robust design (Dehnad 1989, Logothetis and Wynn 1989; Phadke et al., 1983; Phadke, 1989, Shoemaker and Kacker 1988; Taguchi, 1987; Tsui, 1988; Welch et al. 1990). One advantage of constructing fractional factorial designs from a table of orthogonal arrays is that a wide range of numbers of treatment combinations is available. It is reported that since orthogonal arrays were applied in experiments, the result obtained from small scale laboratory experiments have become satisfactorily adapted to the actual manufacturing field. This is because a variable with consistent effect under various conditions of the other variables has a good possibility of reproducing its effect if conditions of the manufacturing scale changes (Wu,1992).

4.6 Randomisation, Blocking and Replication

In this case study, randomisation, blocking and replication which are fundamentals of experimental designs were applied. They form an important part of every experiment because they serve to increase the precision of an experiment.

Randomisation is a procedure for running the experiments in a random order. This is to avoid subjective decisions or other bias and to minimise the effects of unexpected or uncontrollable changes. The order of performing trial runs were selected randomly by allocating each trial run a number, for example number 7, 4, 9 etc and ordering them through these random numbers. Alternatively the numbers could be drawn from a box (or equivalent).

Blocking is the process of grouping the trials of an experiment into subgroups or "blocks". Trials in the same block are performed at the same time or day. The idea is to improve the comparison of treatments by randomly allocating treatments within each block or subgroup. The need to block an experiment can occur under a variety of situations. Suppose the first replicate of experiment in this study was conducted in a different month and a different shift. So to eliminate the effect of inhomogeneity, we use blocking. The design in this case study was divided into two blocks. Each block was run with sixteen experiments.

Replication is simply repeating the basic experiment again. Montgomery (1991) reported that replication has two essential properties. It permits the estimation of the experimental error which forms a basic unit of measurement for determining whether observed differences in the data are really statistically different. It also allows the evaluation of the effect of a factor in the experiment, if the sample mean is used. For instance, if we weld two pieces of metal one using the spot welding method and the other using the arc welding method, and we replicate the experiment n times, then the sample mean has a variance of

$$\sigma_y^2 = \frac{\sigma^2}{n}$$

Suppose y1 and y2 are two observations of strength. If we observed y1=25kN (arc welding method) and y2=27kN (spot welding method) we would probably be unable to make satisfactory inference about the effect of the welding method. That is, the observed difference could be the result of experimental error. But if n was reasonably large, and the experimental error was sufficiently small, then if we observed y2>y1, we could be reasonably safe in concluding that spot welding yields a higher tensile strength than arc welding.

The advantages of replicating the experiment are first, average values have less variability than the individual measurements, so our calculated averages will tend to be closer to the true factor effects. Second, without replication, a single erroneous or unusual sample value can distort the whole analysis. Third, data from replicated experiments can be used to estimate the proportion of variability in the process. This will be discussed further in chapter 5. Last but not least, data from replicated experiments can be used to assess factors that affect the mean level of the process and factors that affect the variability of the process. This will also be discussed in chapter 5.

4.7 Effect of Interactions

We are also interested in estimating important interaction effects. These two–factor interactions (AE, BF, EG, CD, BG) are assigned to columns 6, 9, 10, 12, 15 as shown in Table 4.4 Although orthogonal experimental designs protect against one factor causing an artificially extreme value for the estimated effect of another factor, it does not always alert us to interactions between factors. That is, an estimated factor effect tells us the proportion by which a response changes, on the average, when one factor goes from its low level to its high level. But suppose the average effect of factor A is different when factor B is at its low level than it is when factor B is at its high level. This interaction is averaged out when the average effect for factor A is calculated, and so the estimated effect of factor A gives no clue about the interaction.

The main factors and noise are assigned to the columns as discussed in Table 4.3. The other columns represent interactions between the factors as given in the L16 interaction Table in Appendix 1 (Grove and Davis, 1992). This results in a resolution IV design. That is, the design does not have any main effects mixed with each other or two-factor interactions. However, some two-factor interactions are aliased with other two-factor interactions. When confounding of effects occurs between main factors and two-factor interactions or more, it makes our assessment difficult. We are unable to determine which one is really affecting the response variables. For instance in Appendix 2 column 3, AB is aliased to CE, DF, GH. When two effects are confounded, we say that each is the alias of the other, that is AB=CE=DF=GH. In our case study, we want to know which factors affect the mean. Hence it is essential to assign the factors carefully so that, as far as possible, interactions which are important are not aliased with main effects and will not upset the investigation. Higher order interactions, that is, those involving three or more factors BEF, CDE, ABG etc., do not usually have a large effect. We can see directly from Table 4.4 and Appendix 2 that main factors A, B, C, D, E, F, and G, can easily be determined because they are not confounded with any main factor. This is because we have selected resolution IV of fractional factorial. The level of confounding of an experiment is called its resolution. In our study Resolution IV design was felt to be the most appropriate because we wish to estimate all the main effects and interactions of interest. By considering resolution IV design the main effects are clear of two-factor interactions, yet 2^{8-4} fractional factorial requires only one-sixteen as many experimental run. That is , instead of 256 runs, we only need to run 16 runs. Thus, we would benefit in term of cost and the power of the experiment.

In our case study, a relative humidity was purposely included in the experiment in order to determine the controllable factor level that is least sensitive to noise using average response. By reducing process variability we can better control process and can reduce the cost associated with development, manufacture and use. Lochner and Matar (1990) pointed out that "variability due to the noise factors which are not being controlled can be evaluated by replicating the experiment and calculating standard deviation at each experimental point." Kacker, 1985; Abraham and Mackay 1992 suggested that variability caused by a noise factor can be minimised by exploiting an interaction between the noise factor and some controllable factors. In our case study process variability was evaluated by these two approaches.

4.8 Chapter Summary

In this chapter we discussed the strategy and planning of the design layout for the rubber glove case study. We set up the layout using an integrated approach of the robust concept and sound statistical techniques as presented in chapter 3. These concepts are of special interest in this study. The problems of the manufacturing process have been specified in terms of objectives and factors affecting the process outcome. Both the controllable and noise factors are considered together as a single experiment set-up or combined array. The experimental layouts were structured through the use of orthogonal array and fundamental principles of experimental design. How this experimental design may be used to reduce process or product variability will be demonstrated in chapter 5.

CHAPTER 5

DATA ANALYSIS OF MULTIPLE VARIABLES

5.1 Introduction

This chapter discusses the results of the preliminary data analysis and the data set obtained from the industrial experimentation. The objective of the preliminary data analysis is to study the performance of the current process, and to understand the behaviour of the process. Beside just focusing on factors that affect only the mean response variables, we also examine factors that affect the standard deviation. In this particular case study we also investigate the influence of noise factors in the system. Next, how variability is related to the settings of process parameters is elaborated and used to provide guidelines for selecting process parameters that should minimise variation and maximise the mean. It also presents the standard statistical techniques used and the assumptions imposed on the model. The difficulties due to conflicting levels for some common factors are discussed.

5.2 Preliminary Data Collection

5.2.1 Estimation of Between and within Group Variations

In order to learn more about the glove manufacturing process and product characteristics, preliminary data from the plant was collected. This data allows us to investigate and estimate the type of variations which cause variability in the process. The quality characteristics or response variables considered in the analysis are the

(1) Finger thickness

(2) Tensile strength after ageing

(3) Weight

(4) Pinholes

Once we understand the variability of the manufacturing process, we could then focus our efforts to formulate and implement appropriate corrective actions.

The variation between the group, S_B^2, and within the group, S_W^2, were estimated. The required estimation relationships are given in equation (5.1). This data was collected prior to the experiments and is given in Appendix 3. They were gathered in time order from the production line of interest.

$$n\frac{S_B^2}{S_w^2} = \text{F}-\text{Statistic} \tag{5.1}$$

$$S_B^2 = \frac{\sum_{i=1}^{k}(\bar{x}_{i.} - \bar{\bar{x}}_{..})^2}{(k-1)}$$

$$S_w^2 = \frac{\sum_{i=1}^{k} \mathrm{S}_i^2}{k}$$

$$\mathrm{S}_i^2 = \frac{\sum_{j=1}^{n}(x_{ij} - \bar{x}_{i.})^2}{(n-1)}$$

Where,

S_B^2 = Between group variation
S_w^2 = Within group variation
S_i^2 = Within group standard deviation
n = Sample size (equal)
k = Group size
F − statistic = Ratio between and within group variations
$\bar{x}_{i.}$ = Sample mean of the i'th group
$\bar{\bar{x}}_{..}$ = Overall average of the observations

Substituting the measurements in equation (5.1)

For the tensile strength

n=3, k=25

$$n\frac{S_B^2}{S_w^2} = 3 \times \frac{1.62725^2}{1.40290^2}$$

$$= 4.04$$

For the thickness

n=4, k=80

$$n\frac{S_B^2}{S_w^2} = 4 \times \frac{0.00909^2}{0.01464^2}$$

$$= 1.54$$

For the weight

n=4, k=80

$$n\frac{S_B^2}{S_w^2} = 4 \times \frac{0.12290^2}{0.17421^2}$$

$$= 1.99$$

For the pinholes

n=32, k=60

$$n\frac{S_B^2}{S_w^2} = 32 \mathrm{x} \frac{0.5909^2}{0.6580^2}$$

$$= 25.79$$

For all the four quality characteristics or responses, the estimated variations were greater than one. This suggests that some evidence of additional variability is present in the process. The estimated ratio was then compared to the critical value of the F-statistic to ensure that the additional variations present were not due to chance. Critical value of the test statistic is the point at or above which the null hypothesis can be rejected. From tables, for n=4, and k=80, the critical value is 1.34, while for n=3 and k=25 the critical value is 1.74 and for n=32, and k=60 the critical value is 1.35. Thus these estimations showed that the presence of the additional variability is statistically significant, and suggests that each batch (lot) is different from one another. In this situation, the between group component of variation probably represents special causes of variation such as machine wear, environmental conditions, differences in input variables, etc. These could explain batch to batch glove inconsistencies.

However, there was not much variability within the group of measurements. This information leads to a better appreciation of the behaviour of the glove manufacturing process and product and the type of variations involved.

5.2.2 Process Capability Studies

We are also interested to investigate the Process Capability (6σ) and process performance of the glove manufacturing process. This evaluation can point the way to specific key areas that need detailed examination for potential improvement. Quality requirements are usually given in the form of product specification limits. In our case the specifications for the quality characteristics mentioned earlier, are given as follows:-

Tensile strength	:	Minimum specification limit of 20 Megapascal (MPa)
Finger thickness	:	Minimum specification limit of 0.18 Millimetres (mm).
Weight	:	Minimum specification limit 7.8 Gram (gm) and 8.00 (gm) maximum specification limit.
Pinholes	:	AQL 2.5%

For both the tensile strength and finger thickness only the minimum specification limit is specified. In this situation we could not calculate the Process Capability Index but we can calculate the Process Performance Index. While for the weight we could calculate the process index and the process performance. For the pinholes, only the acceptance quality level is given. We would only calculate the process average ($\bar{\bar{x}}_{..}$).

Process Capability Index

$$C_p = \text{Upper specification limit} - \text{Lower specification limit} / 6\sigma \qquad (5.2)$$

Process Performance Index

$$C_{pk} = \text{Process average} - \text{Lower specification limit} / 3\sigma \text{ or} \qquad (5.3)$$
$$\text{Upper specification limit} - \text{Process average} / 3\sigma$$

Data in Appendix 3 are also used for these calculations:-

Substituting the values in equations (5.2) and (5.3)

For the tensile strength

$\bar{\bar{x}} = 27.13, \ \sigma = 1.4029$

$$C_{pk} = \frac{27.13 - 20.0}{3 \times 1.4029} = 1.69$$

Since the C_{pk} is greater than 1.0 suggesting that the process is producing gloves that conform to the tensile strength specification limit.

For the finger thickness

$\bar{\bar{x}} = 0.2068, \ \sigma = 0.0146$

$$C_{pk} = \frac{0.2068 - 0.180}{3 \times 0.0146} = 0.61$$

The C_{pk} for the finger thickness is less than 1.00 indicating that the process is producing gloves that do not conform to specification. This explains why variation between each lot occurs. To overcome this problem, the company can either change the process average or reduce the variability of the process. The first option seems quite easy to perform in the short term, but in the long run the company has to give away large amount of latex. This might pinch the company since the cost of latex is getting expensive. On the other hand, the second option is to minimise variability in the process. This corrective action will require a study in depth in order to investigate the causes and in long run will benefit the company.

For the weight

$\bar{\bar{x}} = 7.989, \ \sigma = 0.1742$

$$C_p = \frac{8.0 - 7.8}{6 \times 0.1742} = 0.191$$

$$C_{pk} = \frac{0.0107}{3 \text{x} 0.1742} = 0.02$$

The C_{pk} is less than 1.0 suggesting that the process is not capable of manufacturing a glove that will meet the weight specification. It also suggests that some of the individual values are greater than the upper specification and are less than the lower specification. The performance of the process is also less than one indicating that the process is producing gloves that do not conform to the weight specification. This problem becomes worst as the process changes, that is when the process is out-of-control, more waste is produced. We are not quite sure whether the weight specification limits are for the total or average weight of 100 gloves. If the specification is for an individual glove the company has problem. But if otherwise, the company does not need to take any action because the specification has ± 0.20 tolerance while the variation is only 0.17.

<u>For the Pinholes</u>

n=32, k=60, non conforming=18, np = number of non conforming gloves in each subgroup.

we could not calculate the Process Capability, however we could estimate the process average for proportion non conforming $(\bar{p})$.

$$\bar{p} = \frac{(np)1+(np)2+......+(np)m}{n_1+n_2......+n_m}$$

$$= \frac{18}{32 \times 60} \times 100$$

$$= 1\ \%$$

The process average proportion of non conforming product for the pinholes is roughly 1 percent.

The next phase of the investigation is to analyse the data collected from the designed experiments in order to make changes for improvements with respect to robustness and cost. How the data would be analysed will be dealt with in section 5.5-5.8.

5.3 Industrial Experiment Data

5.3.1 Introduction

The experimental study was used to identify two main types of controllable factors; (a) factors which affect standard deviation and (b) factors which affect the mean but not the standard deviation. The controllable factors are factors whose level can be set and maintained. Having identified the two types of factors, the strategy would then be to set factors affecting standard deviation at levels giving minimal variation. The factor which affect the mean and not the standard deviation is used to move the mean to the target. Since changing the factors from low level to high level or vice versa does not affect the standard deviation, this strategy should result in responses which are on target with minimal variation. As mentioned in chapter 4, we are also seeking to find levels of control factors which will minimise the effect of noise factors. In order to discover this, we have included noise factors in the experiment. A noise factor is a factor whose level either cannot or will not be set or maintained, yet which could affect the performance of the output. Noise factors are either difficult, expensive or impossible to control. The ability to distinguish between effects on mean and effects on variability helps to make sound, informed decisions (Lochner and Matar, 1990). In this particular work, rubber gloves have several quality characteristics (multiple quality characteristics) which have equal importance and need to be evaluated simultaneously. The data for the mean and the standard deviation are shown in Tables 5.1 and 5.2.

5.4 Analysis of variance

The standard analysis of variance, ANOVA, is one of the tools used to analyse the results of the combined array designed experiments. As the name suggests, it is used to identify those independent variables which contribute significantly to the variation in the response. Based on these results, we could determine where to set the factors which affect the responses and simultaneously minimise variability in the process. In this procedure, the variation of the response is decomposed and each component is associated with a set of independent variables. The additive fixed effects is the assumed linear model given by equation (5.4)

$$y_{ijk} = \mu_{ij} + \alpha_i + \beta_j + \alpha\beta_{ij} + e_{ijk} \tag{5.4}$$

where,

$i = 1,.....,a$ (factor α)

$j = 1,.....,b$ (factor β)

$k = 1......,n$ (replications)

y_{ijk} = Observed response at the i'th level of α and the j'th level of β in the k replicate

μ_{ij} = Overall mean

α_i = Fixed effect of the i'th level of factor α

β_j = Fixed effect of the j'th level of factor β

$(\alpha\beta)_{ij}$ = Interaction effect of factors α and β

e_{ijk} = Random error associated with i'th j'th observation in the k replicate

The three assumptions about the F-test are listed in decreasing order of importance below.

(1) Errors are independent.

(2) Errors have constant variance.

(3) Errors are Normally distributed.

The first assumption is crucial. It is more than an assumption; it is a requirement that influences the way we conduct our experiment. That is, each trial run in the experiment should not have an effect on any other trial run. This can be achieved by running the whole experiment in a random order to ensure that any treatment combination has an equally likely chance of happening anywhere in the test sequence. Therefore, any systematic variation outside the factors under study is less likely to bias the results. The second assumption is primarily important in the case of unequal sample sizes. In our case study the sample size is equal. For the Poisson distribution $\mu = \sigma^2$. So if the mean level of pinholes varies a lot, than the variance will as well. The third assumption is not generally of major importance. Metcalfe (1994) pointed out that the Normality assumption is not critical because we can depend on the central limit theorem. It has also been widely reported that the F-test is not very sensitive to departures from Normality distributed errors (Glass et al., 1972). This was further emphasised by Ryan and Joiner(1994) and Montgomery (1991), that in practice, both the Normality and constant variance assumptions are not important. Provided the number of observations in each group is about the same, especially in the balanced fixed effects model, the F-test is only slightly affected.

The last two assumptions may be tested or validated. The Normality assumption may be validated using a Normal scores plot, and a simple check of randomness and constant variance assumptions is to plot the residuals e_{ijk} versus the fitted values y_{ijk}. If the assumptions hold, the residuals should be structureless, that is a null plot. In particular, they should be unrelated to any other variables including the predictors. Further discussion on this will be dealt with in the analysis of the experimental data.

The experimental data were analysed for both mean responses and standard deviations by the analysis of variance and graphing the effects that appear to be significant. The following quality characteristics (response variables) were considered in the analysis; pinholes, tensile strength after ageing, finger thickness and weight. After fitting an ANOVA model, graphical displays such as the half Normal plot (also known as a Daniel plot) can be used. This plot helps in the analysis of the experimental data by indicating which effects should be treated as real and which should be treated as arising from random variation. It is also used to determine whether any outliers are affecting the results. Box and Meyer (1985) suggested that outliers are present when points falling near zero appear to follow two different parallel lines rather than one, with negative values on one line and positive values on the other line. Daniel (1959, 1976) also suggested that outliers are detected using half-Normal plots when the intercept of the plot is not zero. Confidence intervals are also considered and discussed to identify the important factors.

Table 5.1 Average Response Table

Rep	Std Order	Rand Order	A	B	C	E	D	F	G	H	AB	AE	BD	BE	BF	BG	CD	y1	y2	y3	y4
1	1	12	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	6.7570	28.2000	0.2236	0.1990
1	2	6	+	–	–	+	–	+	+	–	–	+	+	–	–	–	+	6.9480	27.6000	0.1000	0.1970
1	3	1	–	+	–	+	–	+	–	+	–	–	–	+	+	–	+	7.1660	28.1330	0.2000	0.2020
1	4	15	+	+	–	–	–	–	+	+	+	–	–	–	–	+	+	6.9620	25.5666	0.2000	0.2000
1	5	3	–	–	+	+	–	–	+	+	+	–	+	–	+	–	–	6.6120	27.2660	0.0000	0.1910
1	6	11	+	–	+	–	–	+	–	+	–	–	+	+	–	+	–	7.0970	28.7330	0.2445	0.1900
1	7	10	–	+	+	–	–	+	+	–	–	+	–	–	+	+	–	7.1150	27.5333	0.1414	0.2130
1	8	13	+	+	+	+	–	–	–	–	+	+	–	+	–	–	–	6.9060	26.4000	0.4243	0.1970
1	9	16	–	–	–	–	+	+	+	+	+	+	–	+	–	–	–	7.3560	26.8666	0.2828	0.2030
1	10	2	+	–	–	+	+	–	–	+	–	+	–	–	+	+	–	7.3180	28.3666	0.1000	0.2140
1	11	8	–	+	–	+	+	–	+	–	–	–	+	+	–	+	–	7.7050	28.6330	0.1732	0.2140
1	12	14	+	+	–	–	+	+	–	–	+	–	+	–	+	–	–	7.8770	28.0000	0.2445	0.2210
1	13	7	–	–	+	+	+	+	–	–	+	–	–	–	–	+	+	7.5210	29.9000	0.1000	0.2250
1	14	5	+	–	+	–	+	–	+	–	–	–	–	+	+	–	+	7.4380	24.0000	0.0000	0.2050
1	15	4	–	+	+	–	+	–	–	+	–	+	+	–	–	–	+	7.5230	29.2333	0.2236	0.2150
1	16	9	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	7.4940	27.9333	0.1732	0.2200
2	17	12	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	6.6060	30.5660	0.2000	0.1627
2	18	6	+	–	–	+	–	+	+	–	–	+	+	–	–	–	+	7.0800	25.400	*	0.1689
2	19	1	–	+	–	+	–	+	–	+	–	–	–	+	+	–	+	6.9530	29.2500	0.2000	0.1707
2	20	15	+	+	–	–	–	–	+	+	+	–	–	–	–	+	+	6.6090	26.9000	0.1732	0.1725
2	21	3	–	–	+	+	–	–	+	+	+	–	+	–	+	–	–	6.8510	27.3000	*	0.1746
2	22	11	+	–	+	–	–	+	–	+	–	–	+	+	–	+	–	6.7630	29.8000	0.2828	0.1624
2	23	10	–	+	+	–	–	+	+	–	–	+	–	–	+	+	–	6.9630	27.8000	*	0.1690
2	24	13	+	+	+	+	–	–	–	–	+	+	–	+	–	–	–	6.9240	26.9666	*	0.1794
2	25	16	–	–	–	–	+	+	+	+	+	+	–	+	+	–	–	7.2610	26.3660	0.0000	0.1755
2	26	2	+	–	–	+	+	–	–	+	–	+	–	–	–	+	–	7.4500	30.2660	0.2000	0.1915
2	27	8	–	+	–	+	+	–	+	–	–	–	+	+	+	+	–	7.5660	27.9000	0.1000	0.1797
2	28	14	+	+	–	–	+	+	–	–	+	–	+	–	–	–	–	7.5150	27.2000	0.2445	0.1937
2	29	7	–	–	+	+	+	+	–	–	+	–	–	–	+	+	+	7.3630	28.9330	0.1732	0.1819
2	30	5	+	–	+	–	+	–	+	–	–	–	–	+	–	–	+	7.5370	26.6000	0.1000	0.1882
2	31	4	–	+	+	–	+	–	–	+	–	+	+	–	+	–	+	7.6620	29.0330	0.1000	0.1913
2	32	9	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	7.7910	28.4333	0.2236	0.1997

Note: Rep=Replicates, Std order=Standard Order, Rand order= Random Order, y1= Weight (gm), y2=Tensile strength after ageing (MPa)
y3 = √Pinholes %, y4= Finger thickness (mm), * = missing value

Table 5.2 Standard Deviation Response Table

Replicates	Std Order	Rand Order	A	B	C	D	E	F	G	H	AB	AE	BD	BE	BF	BG	CD	y1	y2	y3
1	1	12	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	-1.7720	-0.3466	-4.42518
1	2	6	+	–	–	+	–	+	+	–	–	+	+	–	–	–	+	-1.7779	0.2712	-4.45718
1	3	1	–	+	–	+	–	+	–	+	–	–	–	+	+	–	+	-2.0174	-0.8764	-4.08251
1	4	15	+	+	–	–	–	–	+	+	+	–	–	–	–	+	+	-1.7720	0.0492	-4.66407
1	5	3	–	–	+	+	–	–	+	+	+	–	+	–	+	–	–	-2.0557	0.0066	-4.50941
1	6	11	+	–	+	–	–	+	–	+	–	–	+	+	–	+	–	-2.1120	0.8051	-4.80790
1	7	10	–	+	+	–	–	+	+	–	–	+	–	–	+	+	–	-1.6094	-0.0135	-4.38067
1	8	13	+	+	+	+	–	–	–	–	+	+	–	+	–	–	–	-1.6094	0.8676	-4.65783
1	9	16	–	–	–	–	+	+	+	+	+	+	–	+	–	–	–	-1.8579	0.8764	-4.31437
1	10	2	+	–	–	+	+	–	–	+	–	+	–	–	+	+	–	-1.8579	0.7059	-4.10652
1	11	8	–	+	–	+	+	–	+	–	–	–	+	+	–	+	–	-1.3243	0.9796	-4.10652
1	12	14	+	+	–	–	+	+	–	–	+	–	+	–	+	–	–	-2.0025	-0.8127	-4.09637
1	13	7	–	–	+	+	+	+	–	–	+	–	–	–	–	+	+	-1.5848	-0.3022	-4.44093
1	14	5	+	–	+	–	+	–	+	–	–	–	–	+	+	–	+	-1.6145	0.8978	-5.24572
1	15	4	–	+	+	–	+	–	–	+	–	+	+	–	–	–	+	-1.7148	0.7457	-4.76792
1	16	9	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-1.6928	0.2836	-4.31751
2	17	12	–	–	–	–	–	–	–	–	+	+	+	+	+	+	+	-1.7148	1.1677	-4.86187
2	18	6	+	–	–	+	–	+	+	–	–	+	+	–	–	–	+	-1.6503	0.8581	-4.96127
2	19	1	–	+	–	+	–	+	–	+	–	–	–	+	+	–	+	-2.3539	-0.0843	-4.81072
2	20	15	+	+	–	–	–	–	+	+	+	–	–	–	–	+	+	-2.3228	1.0655	-4.29754
2	21	3	–	–	+	+	–	–	+	+	+	–	+	–	+	–	–	-1.5799	0.1076	-4.35839
2	22	11	+	–	+	–	–	+	–	+	–	–	+	+	–	+	–	-1.6874	1.0014	-4.55752
2	23	10	–	+	+	–	–	+	+	–	–	+	–	–	+	+	–	-1.9449	-0.2003	-4.59285
2	24	13	+	+	+	+	–	–	–	–	+	+	–	+	–	–	–	-1.9449	-0.1836	-4.25044
2	25	16	–	–	–	–	+	+	+	+	+	+	–	+	+	–	–	-1.8018	0.4236	-5.36467
2	26	2	+	–	–	+	+	–	–	+	–	+	–	–	–	+	–	-1.8018	0.7939	-4.38780
2	27	8	–	+	–	+	+	–	+	–	–	–	+	+	+	+	–	-2.2828	-1.0602	-4.79307
2	28	14	+	+	–	–	+	+	–	–	+	–	+	–	–	–	–	-1.6660	0.4521	-4.69926
2	29	7	–	–	+	+	+	+	–	–	+	–	–	–	+	+	+	-1.7038	-0.1483	-4.72350
2	30	5	+	–	+	–	+	–	+	–	–	–	–	+	–	–	+	-1.8708	1.2790	-4.65321
2	31	4	–	+	+	–	+	–	–	+	–	+	+	–	+	–	+	-1.7487	0.9174	-4.36003
2	32	9	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-1.8326	-0.2695	-4.22489

Note: Std order = Standard order, Rand order = Random order . y1 = ℓn(Weight) gm, y2 = ℓn(Tensile Strength) MPa, y3 = ℓn(Thickness) mm.

5.5 Factors Affecting Mean and Standard Deviation of Pinholes

In this section, we will analyse the response of interest from the designed experiments which was conducted on the rubber glove production line. The mean and standard deviation responses data were given in Table 5.1 and 5.2. The aims of this analysis are: to investigate and identify the controllable factors affecting the product quality. To establish controllable factor levels that will give optimal output. To determine controllable factors that are insensitive to noise. Seven controllable factors and one noise factor at two-levels were investigated in this incomplete randomised block experiment. Letters A to H represents the controllable factors used in the experimental design while product terms BE to CD represent the interactions between factors. Calculations were carried out using the statistical package MINITAB.

Factor A = curing temperature profile
Factor B= latex temperature
Factor C = formers' oven temperature (oven temperature before coagulant dip)
Factor E = humidity
Factor D = percent of calcium nitrate
Factor F = percent of calcium carbonate
Factor G = oven temperature after coagulant dip
Factor H = pH of latex
BE = interaction between latex temperature and humidity
AE = interaction between curing temperature profile and humidity
BF = interaction between latex temperature and percentage of calcium carbonate
BD = interaction between latex temperature and percentage of calcium nitrate
CD = interaction between formers' oven temperature and percent of calcium nitrate,
BG = interaction between latex temperature and oven temperature after coagulant dip.

The following factors are aliased to each other AB=DF=CE=GH, BE=AC=DG=FH, AE=BC=FG=DH, BF=AD=CG=EH, BD=AF=EG=CH, CD=EF=AG=BH, and BG=CF=DE=AH

For the pinholes data, we were quite doubtful of its reliability because of the following reasons. During the second replicate of the experiment, the addition of water to the coagulant tank was very vigorous and the stirrer speed was increased resulting in the creation of bubbles in the tank. The time given to allow the bubbles to settle was also very short. This may explain why more pinholes were found in the second replicate. Thus some of the values of pinholes for the second trial are quite questionable. We decided to leave out some of these values in run number 2, 5, 7 and

8 of second replicate and treated as "missing data". Consequently the results were no longer orthogonal due to the problem that arose in the experiments. To ease handling of the data, the pinhole counts were converted to number of pinholes per 100 pieces of gloves so that they may be treated as continuous variables. Pinhole counts data often follow a Poisson distribution. This is true in our case. This implies that groups with higher average counts also have higher variability, because the mean and the variance in a Poisson distribution are the same. This violates two of our assumptions: Normality and constant variance. A square root transformation of Poisson random variables will stabilise the variance and also provide a variable that has an approximate Normal distribution. The transformation data is Y=√No. of pinholes per 100.

The results from the analysis of variance (ANOVA) for pinholes are displayed in Table 5.3. Before further interpretation of the analysis, the model residuals are checked for model inadequacies. In Figures 5.1 and 5.2, the plots of residuals against the predicted or fitted values and a Normal scores plot are employed to assess the validity of the model assumptions. The plot of residuals against the fitted values as given in Figure 5.1 exhibits some clustering in the middle even though the points of the residuals are scattered within a band of [-0.15,0.15]. This was further checked by plotting a Normal scores plot. The Normal scores of the residuals plotted against the residuals exhibit a reasonable linear fit except for the residuals at the lower and upper ends. This suggests that the assumption of Normality is satisfied. Metcalfe (1994) pointed out that "if errors are Normally distributed we would expect an average of 1 out of 20 standardised residuals to have absolute value larger than 2", so there is nothing remarkable about these two residual points of -2.5, +2.5. A Normal scores plot is a plot of the ordered sample x_i against E $(Z_{(i)})$ which are Normal scores. Any systematic curvature is evidence of departure from Normal distribution.

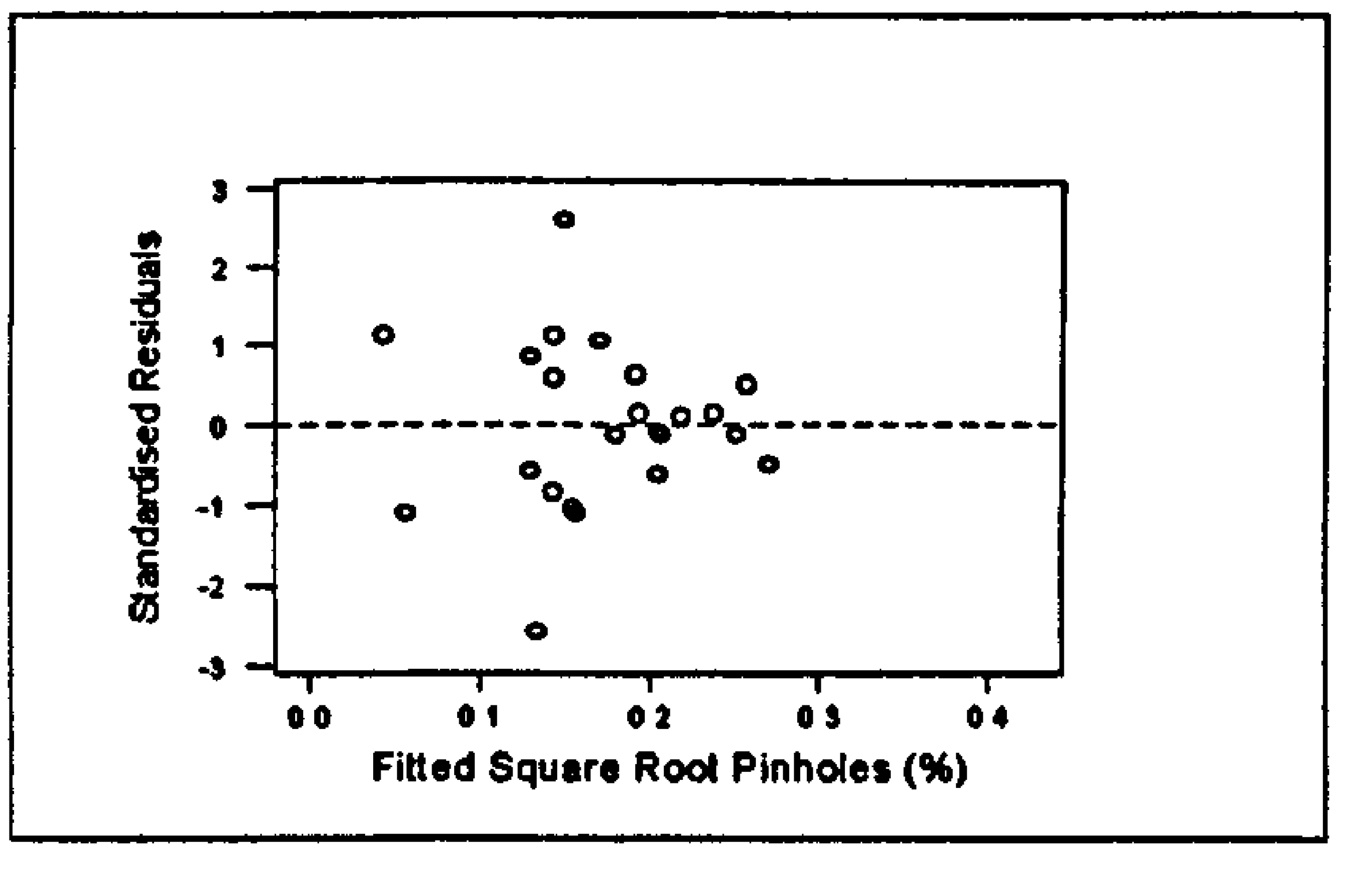


Figure 5.1 Residuals versus Fitted √Pinholes

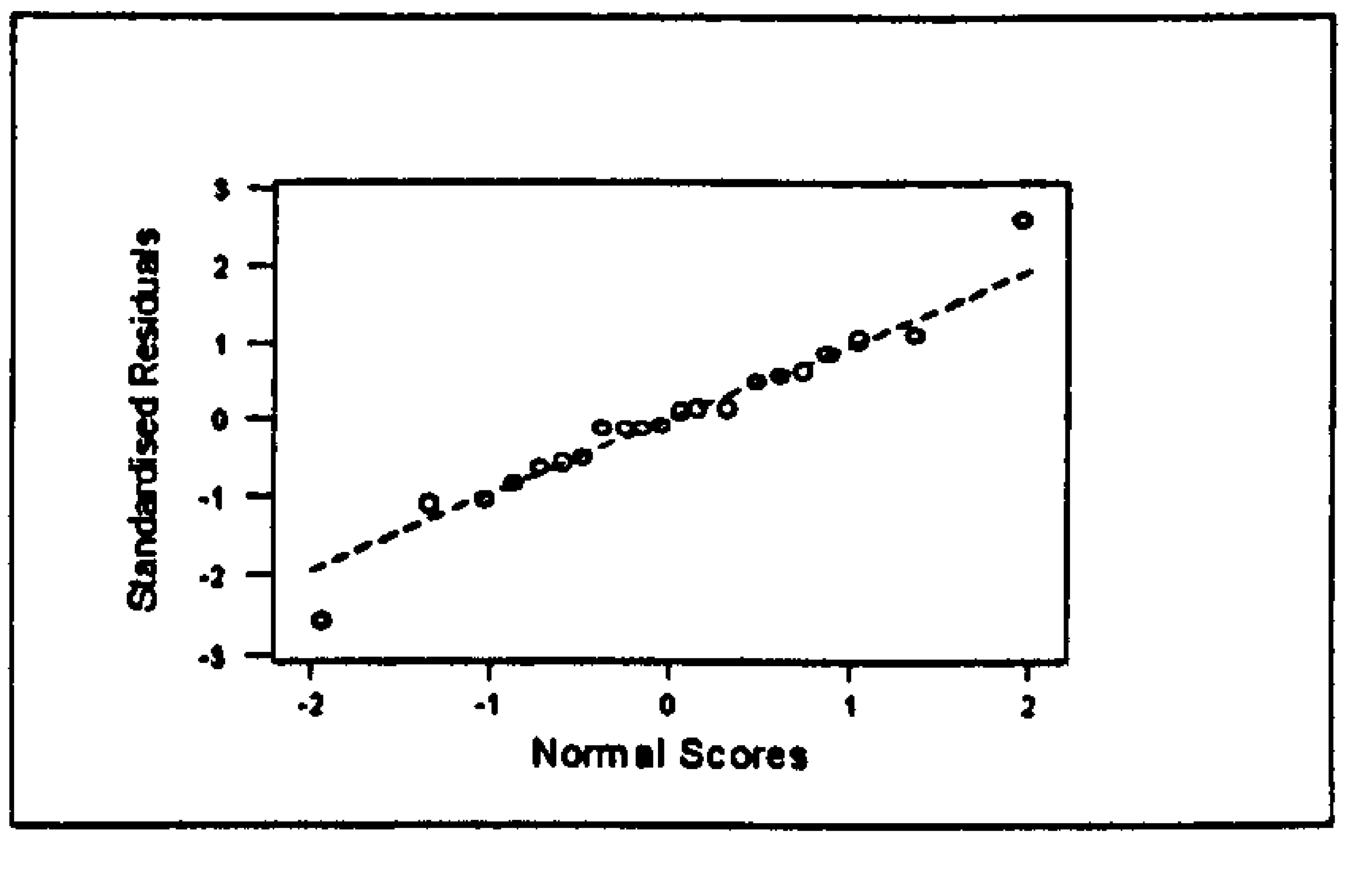


Figure 5.2 Residuals versus Normal scores for √Pinholes

Table 5.3 Analysis of Variance for √Pinholes

Source of variation	DF	Seq SS	Adj SS	Adj MS	F-value	p-value
A	1	0.01261	0.02386	0.02386	4.07	0.069
B	1	0.02372	0.04100	0.04100	7.00	0.023
C	1	0.00033	0.00001	0.00001	0.00	0.971
D	1	0.01470	0.00736	0.00736	1.26	0.286
E	1	0.00046	0.00048	0.00483	0.08	0.779
F	1	0.00593	0.00112	0.00112	0.19	0.671
G	1	0.05030	0.07155	0.07155	12.21	0.005
H	1	0.00071	0.00165	0.00165	0.28	0.606
AB(=DF)	1	0.00972	0.01158	0.01158	1.98	0.187
AE	1	0.00761	0.00864	0.00864	1.48	0.250
BD	1	0.00005	0.00127	0.00127	0.22	0.650
BE	1	0.02186	0.02650	0.02650	4.52	0.057
BF	1	0.01557	0.01258	0.01258	2.15	0.171
BG	1	0.00106	0.00135	0.00135	0.23	0.641
CD	1	0.00662	0.00582	0.00582	0.99	0.340
Block	1	0.00118	0.00118	0.00112	0.20	0.662
Error	11	0.06444	0.06444	0.00586		
Total	27	0.23687				

Note:Significance level (p ≤ 0.05), DF= Degree of freedom, Seq ss= Sequential sum square, Adj ss= Adjusted sum square, Adj MS= Adjusted mean square

The analysis of variance as shown in Table 5.3 revealed that two of the controllable factors, B, G were found to be statistically significant and an interaction effect BE was statistically significant (at $p \leq 0.057$) for the response of the pinholes. This means that there is some evidence that these factors and interaction have influence on the pinholes. In the table, DF is the abbreviation for "degrees of freedom", Seq SS is the abbreviation for "sequential sum of squares", Adj SS is the abbreviation for "adjusted sum of squares", Adj MS is the abbreviation for "adjusted mean square", F is the F-statistic (Adj MS factor/Adj MS error) and p-value is the level of significance. The term 'adjusted' indicates that MINITAB has taken into account additional factors in the model. Although a trial run of 32 experiments were performed for pinholes, we had four "missing data"due to the experimental problem discussed earlier. Thus there were only N=28 observations and the total sequential sum of squares has N-1 (27) degrees of freedom. There were eight factors and two blocks, so adj$SS_{factors}$ and adjSS_{blocks} have seven and one degrees of freedom, respectively. The error or deviation sum of squares is the sum of squares minus the sum of squares for factors and blocks. The sum of squares for error has eleven degrees of freedom. Each sum of squares divided by its degrees of freedom is an adjusted mean square. Therefore to test the equality of factor means, we would use the test statistic

$$F = \frac{AdjMS_{factors}}{AdjMS_{errors}}$$

The tested probability level is 95% (α=0.05). It revealed that factors B (temperature of latex), and G (oven temperature after coagulant dip) are the most important main controllable factors. The critical F-value is ($F_{.05,\ 1\ 11}$) = 4.84. Since factor B has an F value of 7.00 and exceeds 4.84, we could reject the null hypothesis H_0: factor means are the same and accept H_1: factor means are different and conclude that factor B (latex temperature) affects the mean response. Similarly, factor G, has an F-value of 12.21, which exceeds 4.84. Hence factors B and G have large positive effects on the percent of pinholes in the gloves ($p \leq 0.05$). That is, changing the controllable factors from high to low or vice versa changes the average of the response variables. From the ANOVA Table 5.3 we also noted that factor G has the largest effect followed by factor B. While interaction BE, has an F-value of 4.52, and it is statistically significant at $p \leq 0.057$. There is a good reason to suppose that BE has influence on the mean response. Nevertheless, factor A is marginally significant at ($p \leq 0.069$) and has an F-value of 4.07.

An alternative approach to determine which effects should be treated as real and which should be treated as arising from random variation, a half-Normal probability plot is used. The half-Normal probability plot of the 15 contrasts is shown in Figure 5.3. The absolute contrast values are plotted against the half Normal. The values needed to plot Figure 5.3 are given in Appendix 4A. The probability plot uses the variability among the different contrasts to detect the few important effects. This technique is based on the Central Limit Theorem which states that a weighted average of random measurements will be approximately Normally distributed. Effects that lie along the line are negligible, whereas the large effects are far from the line. This plot shows that three points stand away from the line: one interaction BE and two main controllable factors G and B. Since we were doubtful of the effects of B and BE to be treated as real, the large effect G was removed and re-plot the remainder as presented in Figure5.3(b). Again B and BE stood away from the rest of the points.

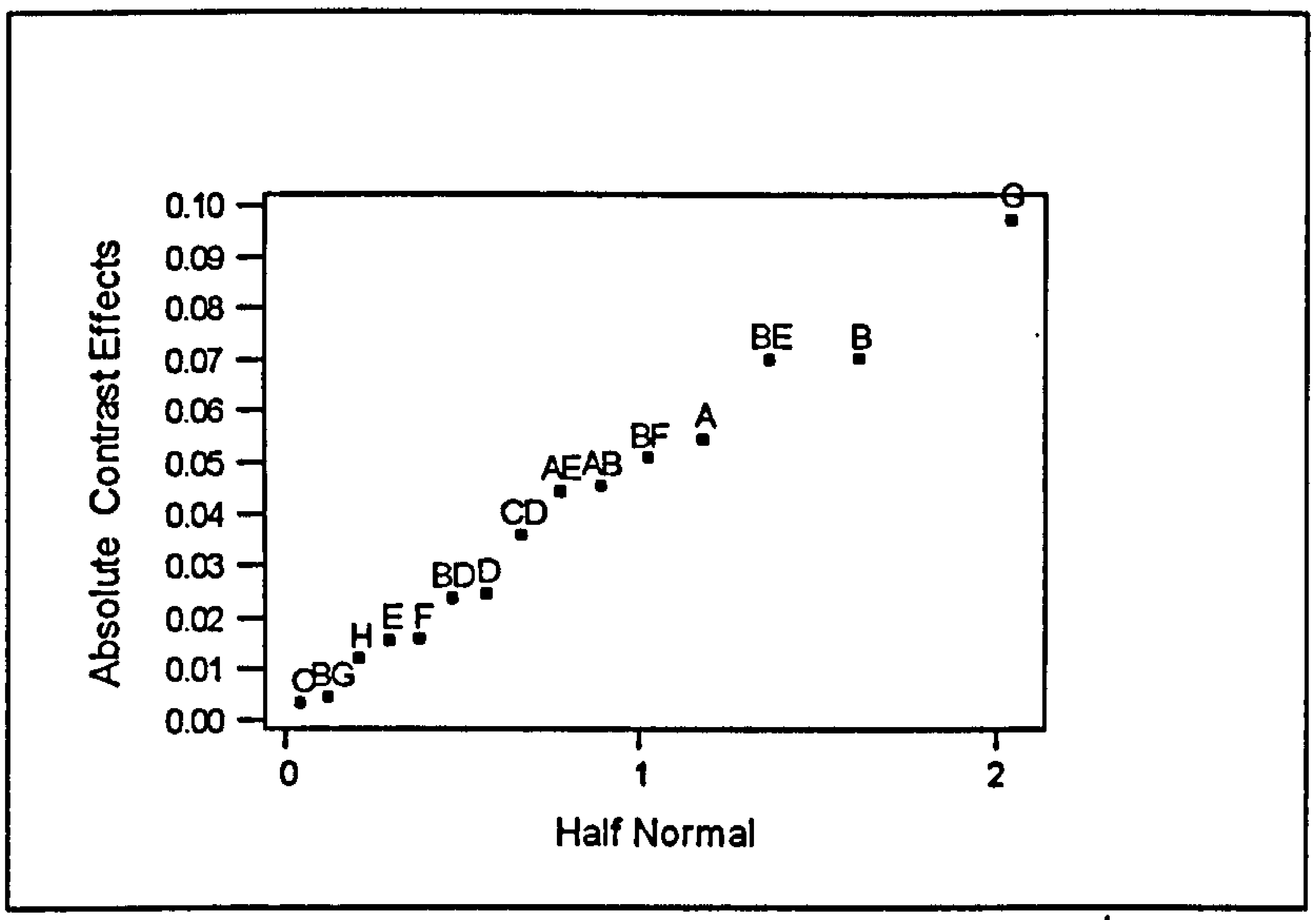


Figure 5.3 (a) Half-Normal Probability Plot of √Pinholes

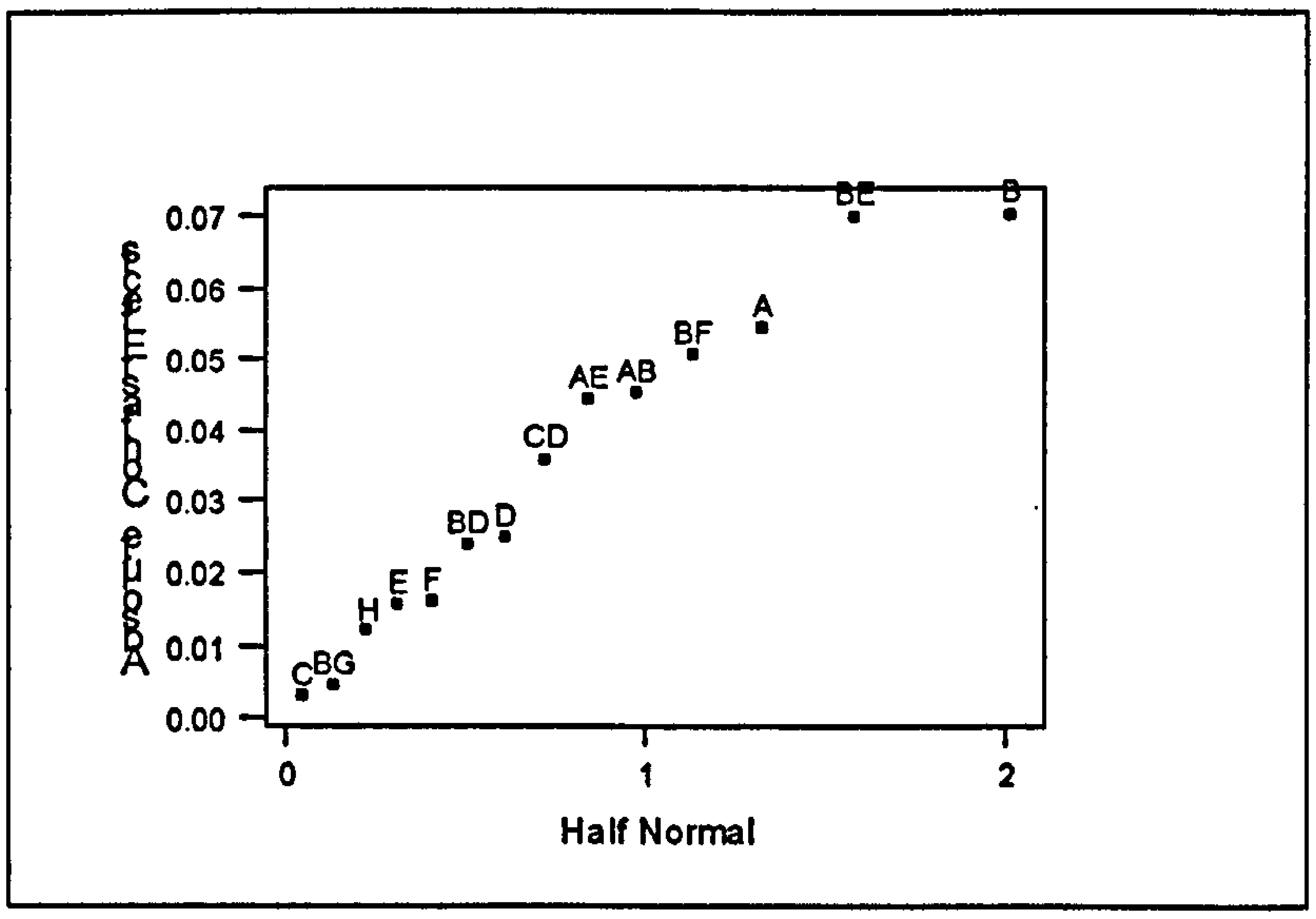


Figure 5.3 (b)Half-Normal probability Plot of √Pinholes

Figure 5.3 Half-Normal Probability Plot of √Pinholes (a) 15 contrasts; (b) 14 contrasts (G removed).

These plots also indicate that factors B, G and BE interaction have real effects on the pinholes of the gloves. Since the intercept of the plot is zero, there is no evidence of outliers. This observation is consistent with the ANOVA analysis.

Although the analysis of variance is a formal way to determine which factor effects are nonzero, we also calculated the standard error of the effects and compare the magnitude of the effects to their standard errors at 95% confidence intervals. For example effect A is $\bar{x}_{A_1}-\bar{x}_{A_2}$, the standard error of each effect is calculated as in equation 5.5. The estimated standard error σ^2 is taken from the ANOVA Table 5.3 by replacing its estimate s^2 and substituting these in equation 5.6

$$\text{Effect of A} \quad = \overline{x}_{A_1} - \overline{x}_{A_2}$$

$$\text{Standard Error of effect} \quad = \sqrt{\operatorname{var}(\overline{x}_{A_1} - \overline{x}_{A_2})}$$

$$= \sqrt{\operatorname{var}(\overline{x}_{A_1}) + \operatorname{var}(\overline{x}_{A_2}) - 2\operatorname{cov}(\overline{x}_{A_1}\overline{x}_{A_2})}$$

$$= \sqrt{\frac{\sigma^2}{n_1} + \frac{\sigma^2}{n_2}} = \sqrt{\frac{2\sigma^2}{14}}$$

$$= \sqrt{\frac{\sigma^2}{7}} \tag{5.5}$$

$$= \sqrt{\frac{0.00586}{7}} = 0.029$$

95% Confidence Interval for the effect A is

$$\overline{x}_{A_1} - \overline{x}_{A_2} \pm t_{n-1;[\alpha/2]}\sqrt{\frac{\sigma^2}{7}} \tag{5.6}$$

A is 0.0547 ± 0.064.

The remainder of the effects are calculated in the similar manner. In case of pinholes we had only 28 runs and for the weight, the finger thickness and tensile strength we had 32 runs, where n is the number of average observations, n=16. This analysis indicates that there is some evidence factors G, B, and BE interaction are important as they are the only factor effect estimates for which the interval do not include zero. This can be shown below:-

Factor	95% Confidence Intervals	Factor	95% Confidence Intervals
C	0.0032 ± 0.064	CD	0.0359 ± 0.064
BG	0.0045 ± 0.064	AE	0.0445 ± 0.064
H	0.0120 ± 0.064	AB	0.0454 ± 0.064
E	0.0157 ± 0.064	BF	0.0509 ± 0.064
F	0.0160 ± 0.064	BE	0.0703 ± 0.064
BD	0.0237 ± 0.064	B	0.0705 ± 0.064
D	0.0246 ± 0.064	G	0.0970 ± 0.064

A follow-up analysis of Table 5.3 is summarised in Figure 5.4 and 5.5, showing graphical representations of the estimated effects (based on contrast effects). This graphical technique has been used by Kacker and Shoemaker (1986), Phadke (1987) and Barker (1986). The integers 1 and 2 denote low and high levels of the factors. The estimated main effect is calculated by noting the difference between the 1 (low) level of B and the average response at the 2 (high) level of B, as given below :-

Table 5.4 Main Effects of Factors B, and G on √Pinholes

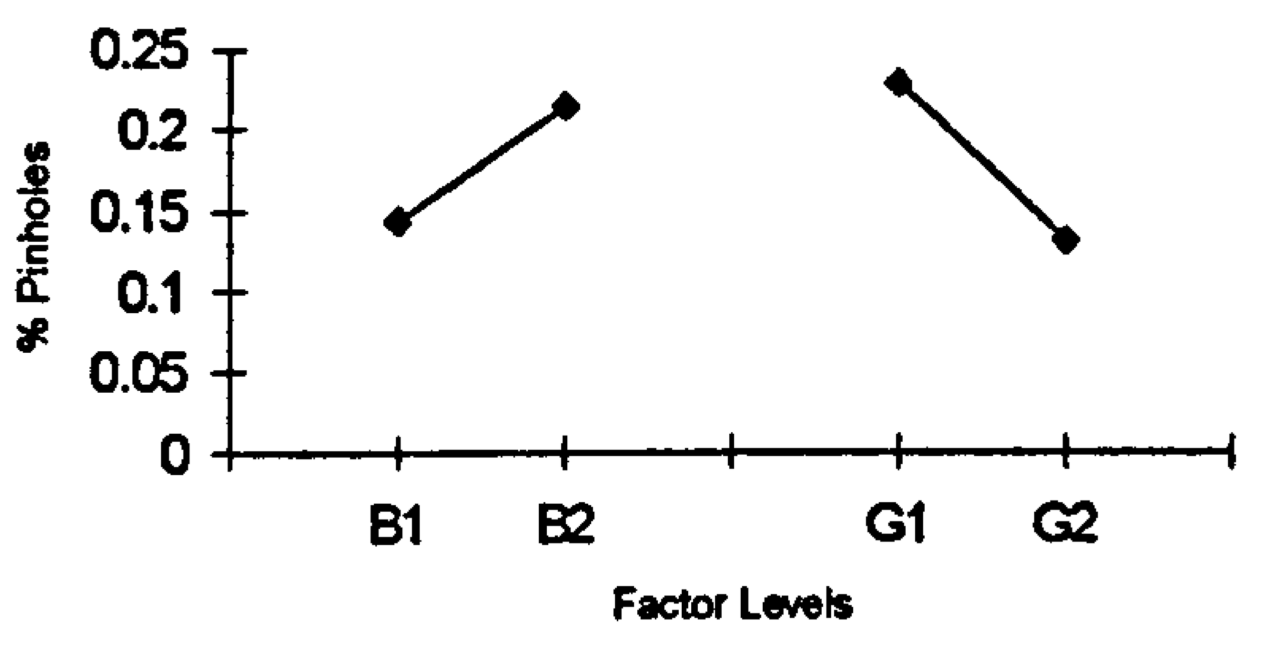
Levels	Factors	
	B	G
Average Response at High Level (2)	0.2140	0.1301
Average Response at Low level (1)	0.1434	0.2273
Main Effect	0.0706	0.0972

Figure 5.4 is plotted based on these estimated effects. These results suggested that pinholes would be reduced when factor B_1 (temperature of latex) is set low and factor G_2 (oven temperature after coagulant dip) set high. This diagram shows that factor G has larger effect than B, which is also observed in the ANOVA Table 5.3. No significant interaction effect was found between the main controllable factors. The remaining controllable factors C, D, F and H do not appear to be statistically significant within the range of the experimental conditions. Hence, these controllable factors should be set at low levels due to economical reasons (low consumption of chemical means less manufacturing cost and a lower temperature means less energy usage). It is also interesting to note that there is a significant interaction between factor B (temperature of latex) and factor E (humidity). As mentioned earlier, we are also interested in finding a factor level that will minimise the effect of the noise factor, humidity. When we examine the effect of factor B at different levels of E, there is difference in the response at all levels of E as presented in Table 5.5.

Calculations for interaction plots are also discussed in Ott (1975), Daniel (1976) and Box, Hunter and Hunter (1978). The orthogonality of our test plan assures a balanced comparison. This was not true in our pinhole data due to reasons discussed earlier.

B_1(Low)	B_2(High)	
0.187	0.187	E_1(Low)
0.100	0.241	E_2(High)

Table 5.5 Interaction Effect of BE on √Pinholes



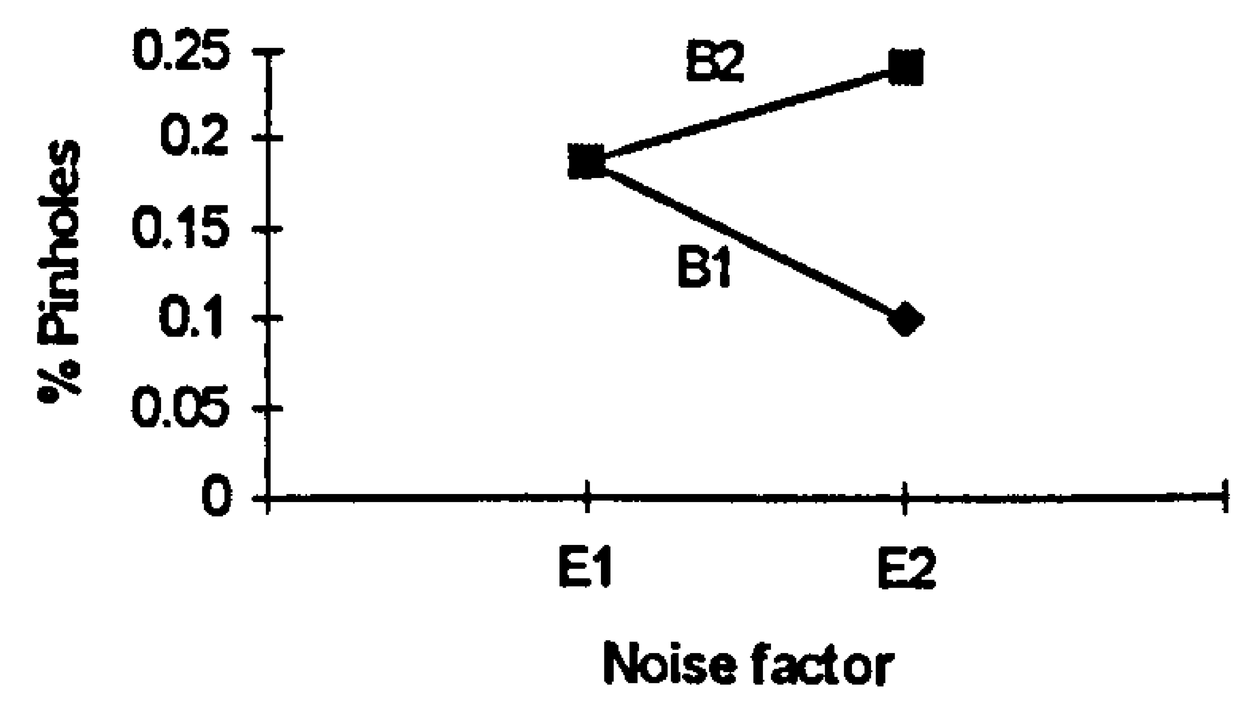


Figure 5.4 Main Effects for √Pinhole   Figure 5.5 Interaction Effect for √Pinholes

In Figure 5.5, the interaction between factor B and E averages are plotted, and the lack of parallelism indicates the presence of interaction effects. The discovery of interaction is very important information because we can understand the process better. Examination of Table 5.5 showed that interaction at $B_1 E_2$ yields less pinholes. This implies that factor E has significant effect and contributes to variability in the process at some settings of the controllable factors. Thus, it is important to find settings of the controllable factors at which the effect of factor E is small. It appears that there is less percent of pinholes when the latex temperature (B) is set low (factor B_1) and humidity (E) is set high as given in Figure 5.5. The goal here is to minimise the percent of pinholes and minimise variability. However, humidity (E) is a noise factor which cannot be controlled. We can see from Figure 5.5 that when humidity is low, setting factor B either low or high would yield similar percent of pinholes. This indicates that factor B has almost no effect on average response when humidity is at low. But when humidity moves from low to high, we observed that B_1 at low temperature % of pinholes drops from 0.187 to 0.099. Thus, there is a decrease of pinholes by 47.05 % but variation in the percent of pinholes is increased . This is shown in Figure 5.5, where B_1 has bigger slope as compared to B_2. On the other hand, if factor B_2 is set at the high level, the % of pinholes increases by 28.87% but variability is small. There is a conflict between levels that minimise average pinholes and levels that minimise variability. Since the % of pinholes is significantly reduced if we set at B_1, it would probably be best to set B low. Thus by examining interaction effects we discovered that information about the BE interaction in this case is more useful than knowledge of the main effects on their own. Factor B affects both the average and standard deviation of the response. Even though it is important to reduce variability, the potential reduction in pinholes in the variability is small (28.9 %) compared to the potential reduction in the number of pinholes, which is greater (47.1%). Thus, we have to trade off variability in this case.

5.6 Factors Affecting Mean and Standard Deviation of Strength

The next quality characteristic that we studied was tensile strength. An analysis of variance was performed to determine if the different factor levels affect tensile strength. A complete response table for this data appears in Table 5.1. Examination of the ANOVA Table 5.6 suggested that the main controllable factor G (oven temperature after coagulant dip) was statistically significant with an F-value of 26.57 at ($p \leq 0.01$). The next largest observed effect is BG interaction (latex temperature and oven temperature after coagulant dip) with an F-value of 14.49. Factor A was found statistically significant with an F-value of 8.00 at ($p \leq 0.013$). Though BD interaction was statistically significant (at $p \leq 0.045$) and had high F-value of 4.76, it was not considered significant. This is because both factors B and D themselves were not statistically significant. According to Box and Meyer (1985) if the main factors are not significant, their interaction is not significant. Moreover, the BD interaction effect when examined at each of the low and high levels tends to cancel the effect of each other, this can be shown by a plot of the BD interaction in Figure 5.6.

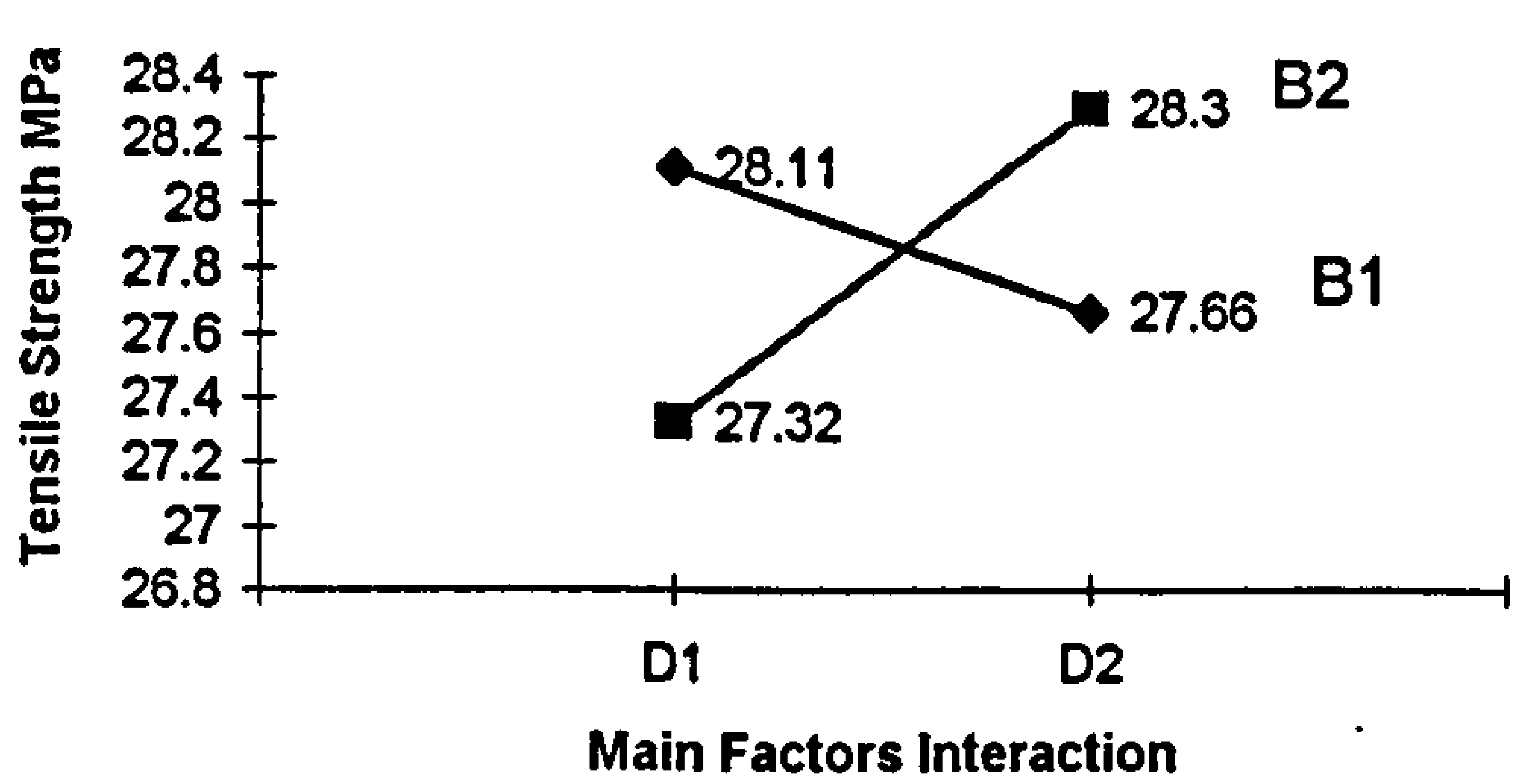


Figure 5.6 BD Interaction Effect for Mean Tensile Strength

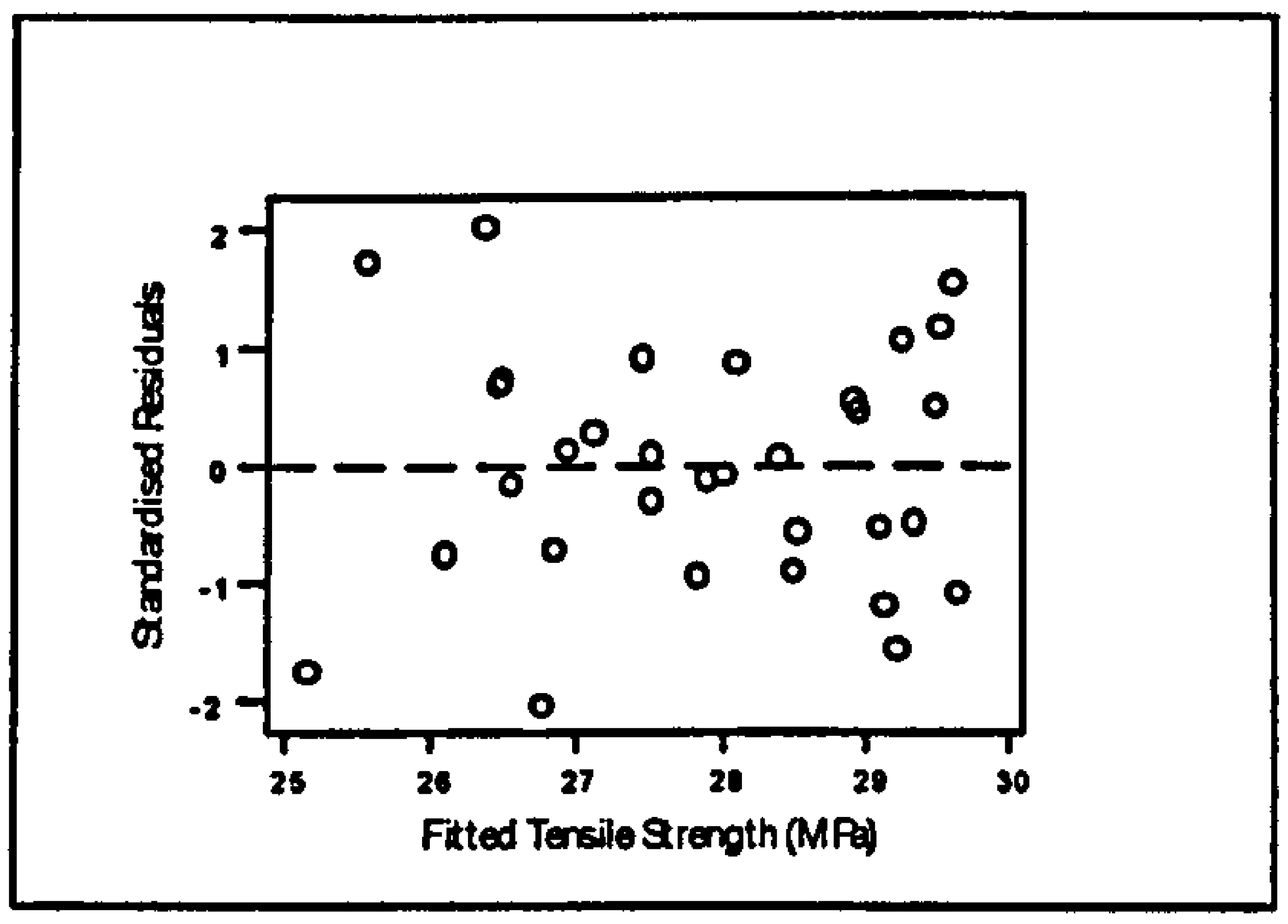
Therefore from the analysis, we found that there is some evidence that the tensile strength is affected by the oven temperature after coagulant dip (G), and curing temperature profile (A) and BG interaction. The effect of these factors are also known as location effects. The rest of the factors including the interaction terms appear not statistically significant at ($p \leq 0.05$).

Table 5.6 Analysis of Variance for Mean Tensile Strength

Source of variation	DF	Seq SS	Adj SS	Adj MS	F-value	P-value
A	1	6.7968	6.7968	6.7968	8.00	0.013
B	1	0.0487	0.0487	0.0487	0.06	0.814
C	1	0.0132	0.0132	0.0132	0.02	0.902
D	1	0.5643	0.5643	0.5643	0.66	0.428
E	1	1.2336	1.2336	1.2336	1.45	0.247
F	1	0.6857	0.6857	0.6857	0.81	0.383
G	1	22.5832	22.5832	22.5832	26.57	0.000
H	1	1.9085	1.9085	1.9085	2.25	0.155
AB(=DF)	1	0.9398	0.9398	0.9398	1.11	0.310
AE	1	0.2537	0.2537	0.2537	0.30	0.593
BD	1	4.0493	4.0493	4.0493	4.76	0.045
BE	1	0.0719	0.0719	0.0719	0.08	0.775
BF	1	0.2139	0.2139	0.2139	0.25	0.623
BG	1	12.3127	12.3127	12.3127	14.49	0.002
CD	1	0.0025	0.0025	0.0025	0.00	0.957
Block	1	1.2598	1.2598	1.2598	1.48	0.242
Error	15	12.7484	12.7484	0.8499		
Total	31	65.6861				

Note:Significance level ($p \leq 0.05$), DF= Degree of freedom, Seq ss= Sequential sum square, Adj ss= Adjusted sum square, Adj MS= Adjusted mean square

The adequacy of the model for tensile strength was again assessed by simply plotting the residuals against the fitted values as shown in Figure 5.7. The structureless residuals verified that the Normality assumptions, constant variance and randomly scattered points are valid and therefore the model is adequate. This is further emphasised by the plot of residuals against the Normal scores. It was observed that the residual points in Figure 5.8 lie approximately on a straight line (the dashed line) exhibiting a good linear fit. The two plots confirmed that the assumptions about the residuals are satisfied.



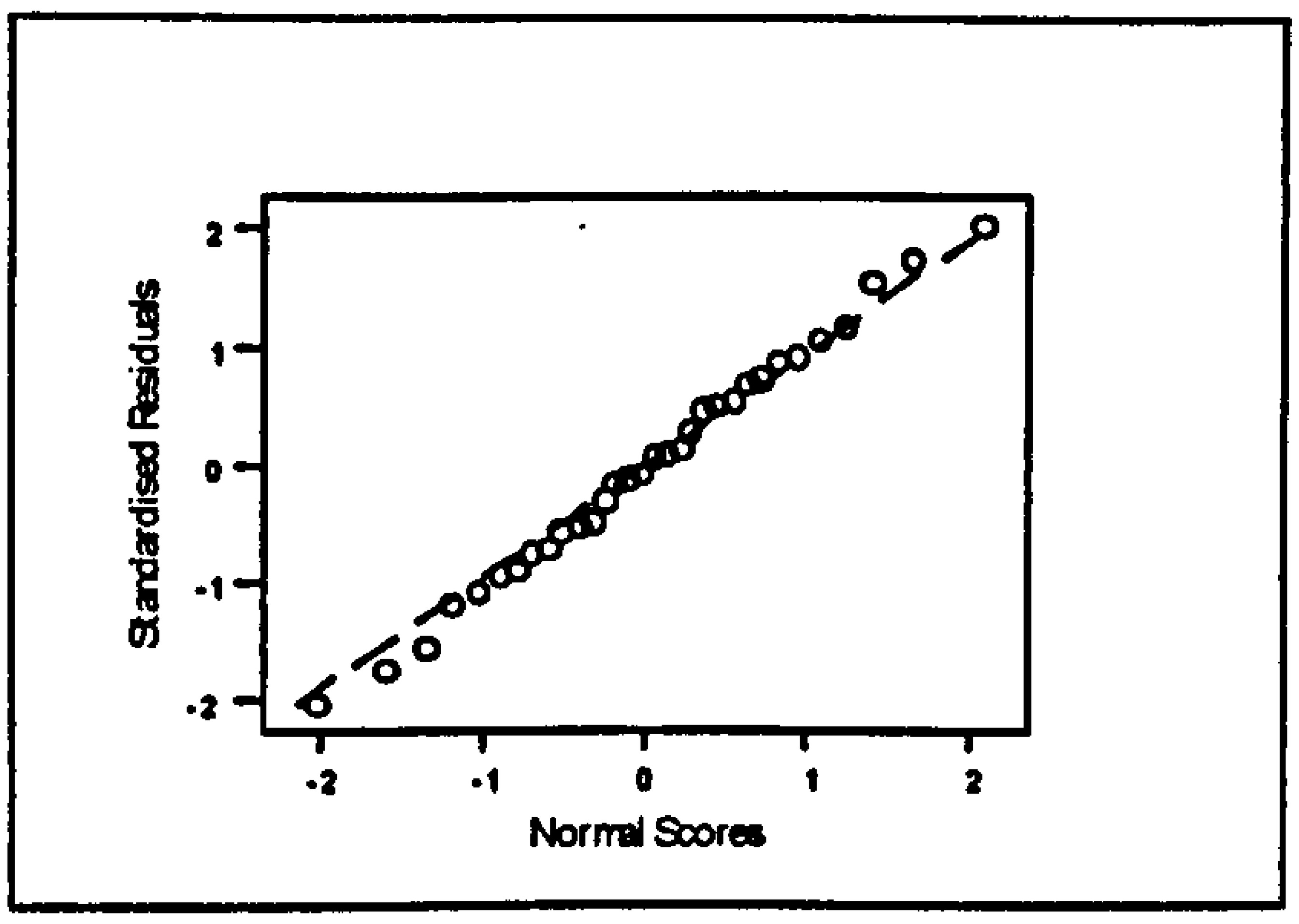


Figure 5.7 Residuals versus Fitted Tensile strength

Figure 5.8 Residuals versus Nscores Tensile Strength

Again a half-Normal probaility plot is used to determine which effects should be treated as real and which should be treated as arising from random variation. The half-Normal probability plot of the 15 contrasts is shown in Figure 5.9. The absolute contrast values are plotted against the half Normal scores. The values needed to plot Figure 5.9 are given in Appendix 4B. Figure 5.9(a) shows half-Normal probability plot of 15 contrast values of the mean strength. It indicates that four points are separated from the others. We noted that factors G, A and BG, BD interactions are the important mean effects. We then removed the largest effect G and replot with 14 contrast values as shown in Figure 5.9(b). Again BG, A, and BD stood away from the rest of the points. But BD was not considered in this case as discussed earlier. The overall near linear appearance of the plot suggests that the remainder of the factors appear to be insignificant.

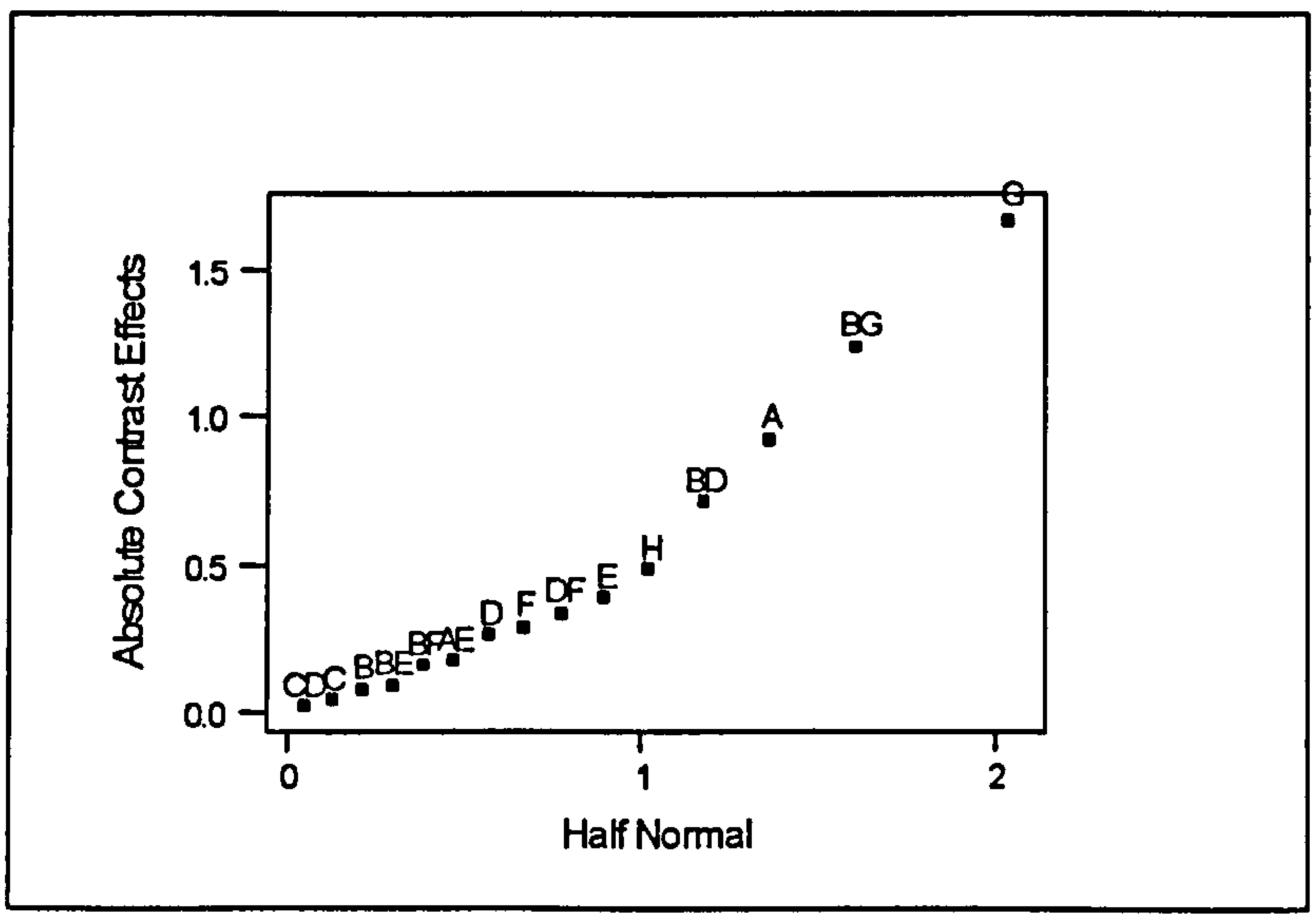


Figure 5.9(a) Half-Normal Probability Plot of Mean Strength

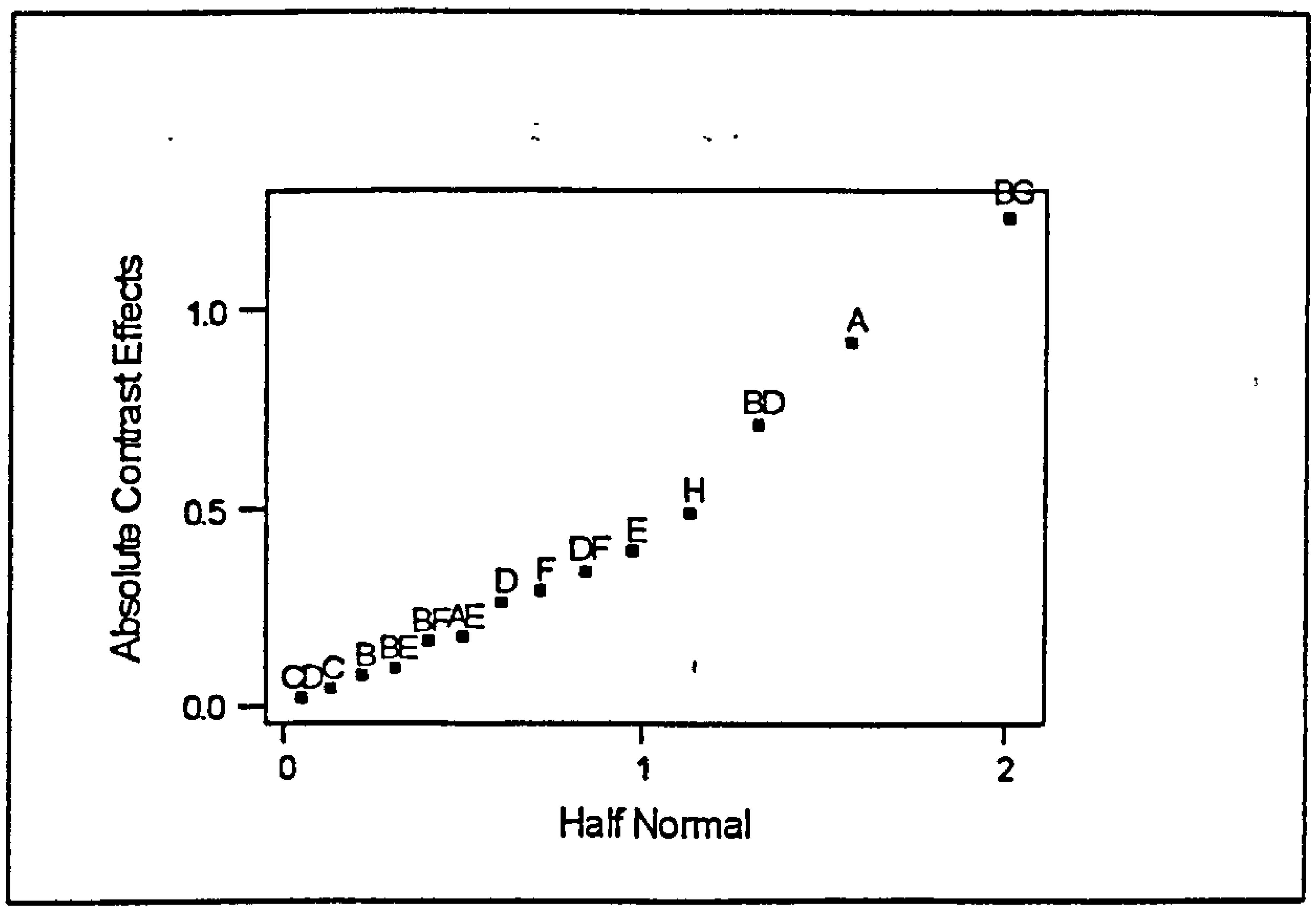


Figure 5.9(b) Half-Normal Probability Plot of Mean Strength

Figure 5.9 Half-Normal Probability Plot of Mean Strength (a) 15 contrasts; (b) 14 contrasts (G removed)

We have also calculated the estimated standard error by replacing σ^2 by its estimate s^2 given by the error mean square in the ANOVA Table 5.6 and substituting these in equations 5.5 and 5.6. These intervals are approximately 95% Confidence Intervals. This analysis confirms that there is some evidence that factors G, BG, A, and BD interaction are important as they are the only factor effect estimates for which the intervals do not include zero. The BD interaction has been ignored as discussed earlier.

Factor	95% Confidence Intervals	Factor	95% Confidence Intervals
CD	0.0178 ± 0.689	DF	0.3428 ± 0.689
C	0.0408 ± 0.689	E	0.3927 ± 0.689
B	0.0780 ± 0.689	H	0.4884 ± 0.689
BE	0.0948 ± 0.689	BD	0.7114 ± 0.689
BF	0.0948 ± 0.689	A	0.9218 ± 0.689
AE	0.1781 ± 0.689	BG	1.2406 ± 0.689
D	0.2656 ± 0.689	G	1.6847 ± 0.689
F	0.2656 ± 0.689		

A follow-up analysis of Table 5.7 was performed. Factors having strong effects on mean tensile strength is shown in Table 5.7. We are tempted to interpret the main effects separately which in this case could be quite misleading. This is because of the presence of interaction effect between factor B and G. The estimated effects (based on contrast effects) of this interaction are further summarised in Table 5.8. A graphical representation of the estimated effects of the interaction is shown in Figure 5.11.

Table 5.7 Main Effects of Factors A and G on Mean Strength

Levels	Factors	
	A(MPa)	G (MPa)
Average Response at High Level (2)	27.385	27.006
Average Response at Low level (1)	28.307	28.686
Main Effect	0.915	1.680

G_1(Low)	G_2(High)	
29.346 MPa	26.425 MPa	B_1(Low)
28.027 MPa	27.587 MPa	B_2(High)

Table 5.8 Interaction Effect of BG on Mean Tensile Strength

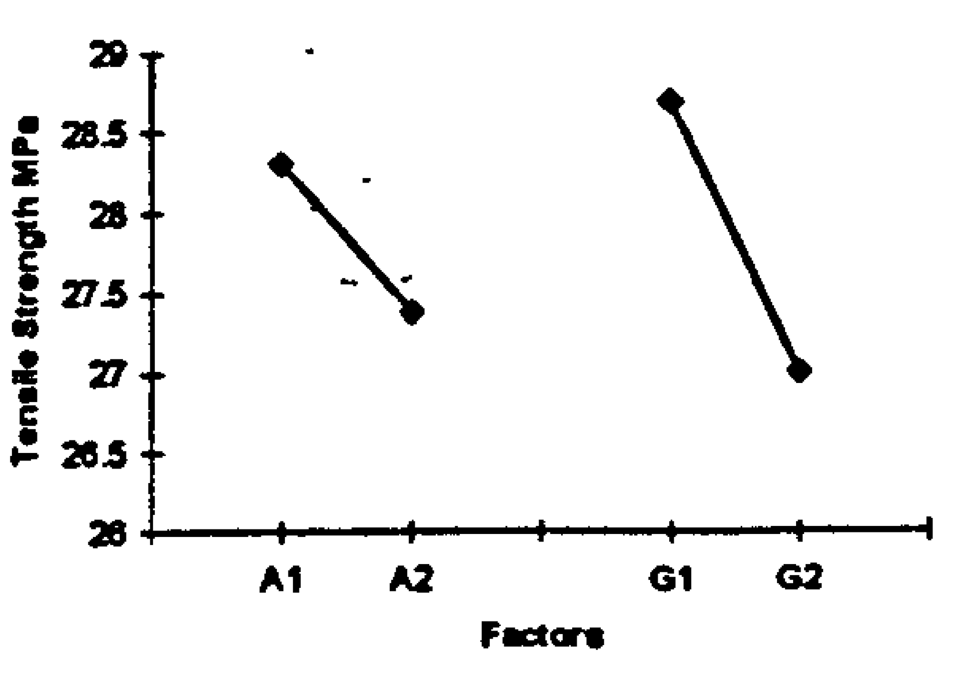


Figure 5.10 Main Effects for Tensile Strength

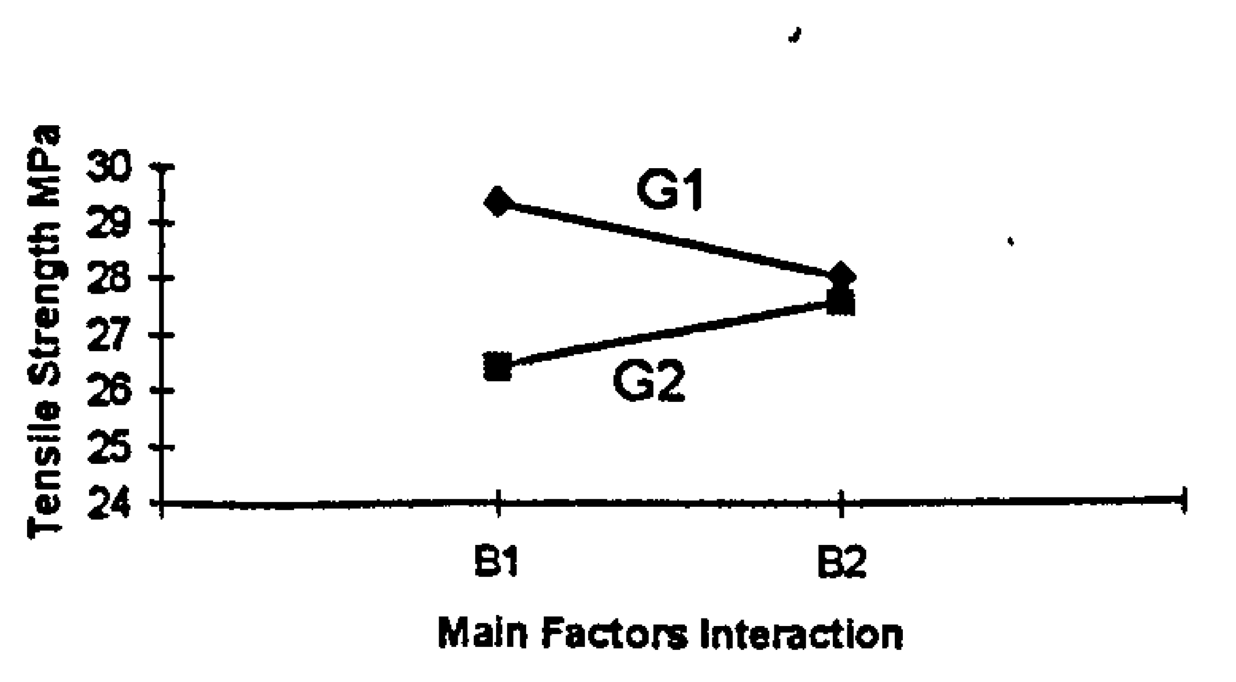


Figure 5.11 Interaction Effects for Tensile Strength

Figure 5.10 revealed that when oven temperature after coagulant dip (G) and curing temperature profile (A) are set at their low levels, the highest average tensile strength was achieved. However, a significant interaction was found between the main controllable factors, latex temperature (B) and oven temperature after coagulant dip

(G). This interaction is important. Although factor B is not significant by itself, its interaction with factor G which is highly significant, requires B to be considered. Figure 5.11 indicates that setting factors G and B at low is the optimal choice in order to maximise the mean strength. The rest of the factors B, C, D, E, F and H have very small F-values and appear to be insignificant. They should be set at their most economical levels which is at their low levels.

We have focused on finding which factor level result in differences between the means. We are also interested in investigating whether the different factor levels affect variability; that is, we are interested in discovering potential dispersion effects, using standard deviation as the response variable. This is because we want to have a consistent product. For instance, if the average thickness of the glove is increased by ten percent, but is uneven, then this is not necessarily better.

Noise factors which are considered critical are treated just like control factors. Variability due to the noise factors which are not being controlled are evaluated by replicating the experiment and calculating sample standard deviations at each trial run. From the experiments we collected 10 pieces of gloves for each trial run. Logarithms of the sample standard deviation are used instead of the standard deviation because as mentioned earlier, the Central Limit results in response variables which are roughly Normally distributed. When this happens, the sample means and effects are also approximately Normally distributed, but the standard deviations are not. Nevertheless, if we transform the sample standard deviations by taking the natural log they will be much closer to being Normally distributed.

The data for standard deviation from the experiment is tabulated in the response Table given in Table 5.2. The results from the ANOVA computations for the standard deviation of tensile strength are given in Table 5.9. The F-tests showed that only factor A is statistically significant for the tensile strength with an F-value of 5.28 (at $p \leq 0.036$). Factor A appears to have the largest effect as compared to the rest of the effects. There is some evidence that factor A affects process variability. That is, changing the levels of the curing oven profile would influence the process variability.

Table 5.9 Analysis of Variance for ℓn(SD)strength

Source of variation	DF	Seq SS	Adj SS	Adj MS	F-value	p-value
A	1	2.0674	2.0674	2.0674	5.28	0.036
B	1	0.3304	0.3304	0.3304	0.84	0.373
C	1	0.2072	0.2072	0.2072	0.53	0.478
D	1	0.1590	0.1590	0.1590	0.41	0.534
E	1	1.1773	1.1773	1.1773	3.00	0.104
F	1	1.0379	1.0379	1.0379	2.65	0.124
G	1	0.4145	0.4145	0.4145	1.06	0.320
H	1	0.0122	0.0122	0.0122	0.03	0.862
AB(=DF)	1	0.2441	0.2441	0.2441	0.62	0.442
AE	1	0.0286	0.0286	0.0286	0.07	0.791
BD	1	0.1538	0.1538	0.1538	0.39	0.540
BE	1	0.1520	0.1520	0.1520	0.39	0.543
BF	1	0.0195	0.0195	0.0195	0.05	0.826
BG	1	0.0000	0.0000	0.0000	0.00	0.998
CD	1	0.0299	0.0299	0.0299	0.08	0.780
Block	1	0.0309	0.0309	0.0309	0.08	0.783
Error	15	5.8788	5.8788	0.3919		
Total	31	11.9436				

Note:Significance level ($p \leq 0.05$), DF= Degree of freedom, Seq ss= Sequential sum square, Adj ss= Adjusted sum square, Adj MS= Adjusted mean square

The adequacy of the fitted model is verified by plotting the residuals against fitted values as shown in Figure 5.12. These residuals are randomly distributed, with constant variance[2.5, -2.5]. The Normal scores plot shown in Figure 5.13 also revealed that the residuals lie approximately along a straight line (the dashed line) with the exception of one point on the upper and lower end. This suggests that the residuals are Normally distributed and there are no indications of unusual residuals.

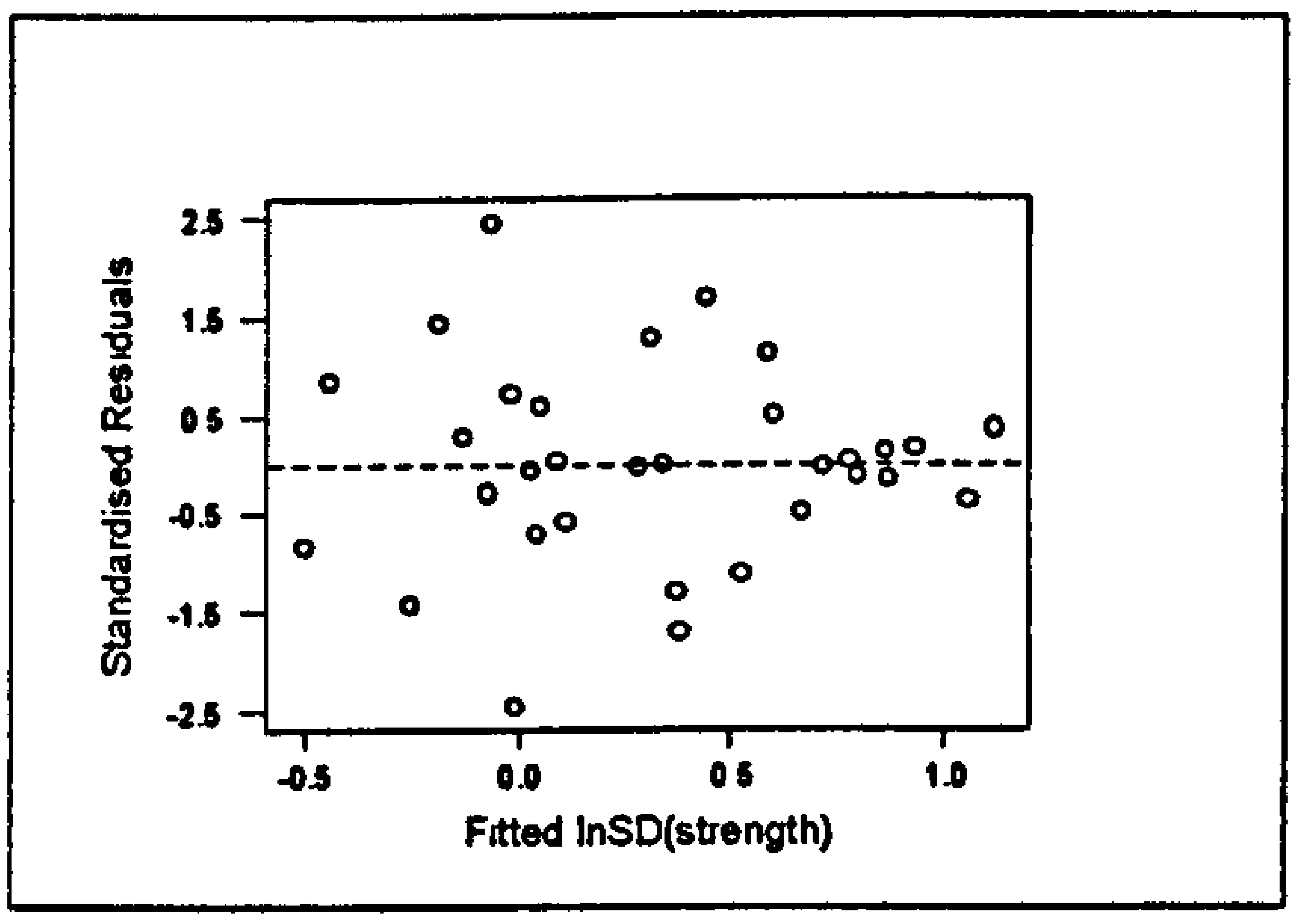


Figure 5.12 Residuals versus Fitted of ℓn(SD)strength

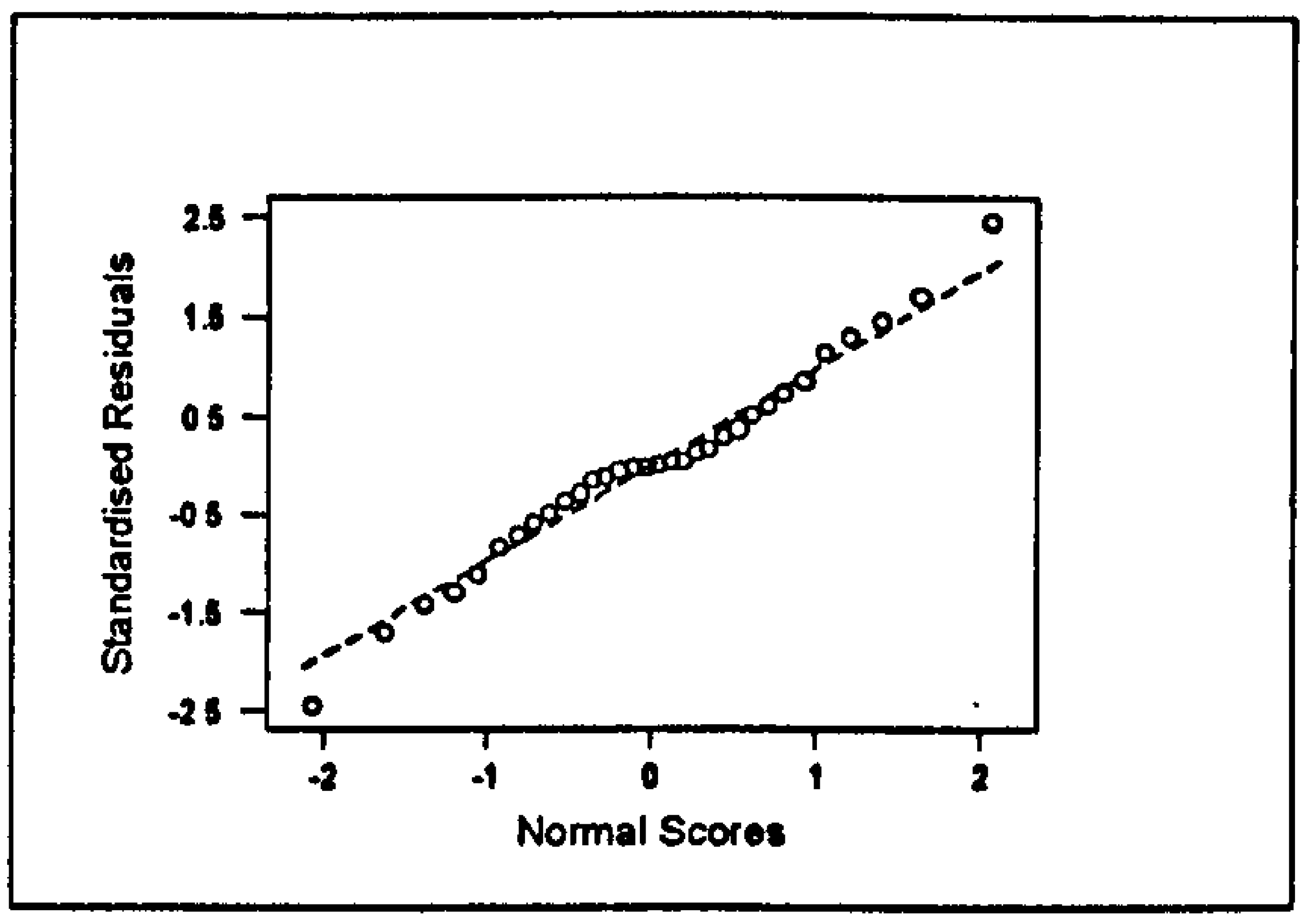


Figure 5.13 Normal Scores Plot of ℓn(SD)strength

Again we performed the 95% Confidence Intervals on the standard deviation (dispersion effect) using equations (5.5) and (5.6) and the analysis is shown below: The analysis also indicates that factor A is the only factor estimates for which the intervals do not include zero. This analysis confirms that there is some evidence that factor A is affecting the process variability.

Factor	95% Confidence Intervals	Factor	95% Confidence Intervals
BG	0.0005 ± 0.4712	C	0.2444 ± 0.4712
H	0.0407 ± 0.4712	DF	0.1747 ± 0.4712
BF	0.0494 ± 0.4712	B	0.2032 ± 0.4712
AE	0.060 ± 0.4712	G	0.2277 ± 0.4712
CD	0.0613 ± 0.4712	F	0.3602 ± 0.4712
BE	0.1379 ± 0.4712	E	0.3836 ± 0.4712
BD	0.1387 ± 0.4712	A	0.5084 ± 0.4712
D	0.1410 ± 0.4712		

Next we investigate the level of factor A which affects the variability of the glove strength. Figure 5.14 was constructed at each factor level for the main effect. The estimated effect of factor A is presented graphically in Figure 5.14. Examination of this plot reveals that when factor A moves from low to high the variability in the process increases. Consequently factor A is a dispersion effect. It should be set at low to minimise process variability. That is the standard deviation response will increase if factor A is high. It is also observed that factor A influences both the mean and process variability. Therefore factor A cannot be used as adjustment factor. Controllable factors C, F, G and H do not apparently effect either the mean or standard deviation of the tensile strength. This means that they can be adjusted to any desired level without affecting the process average or process variability. Hence, they should be set at economical operating level.

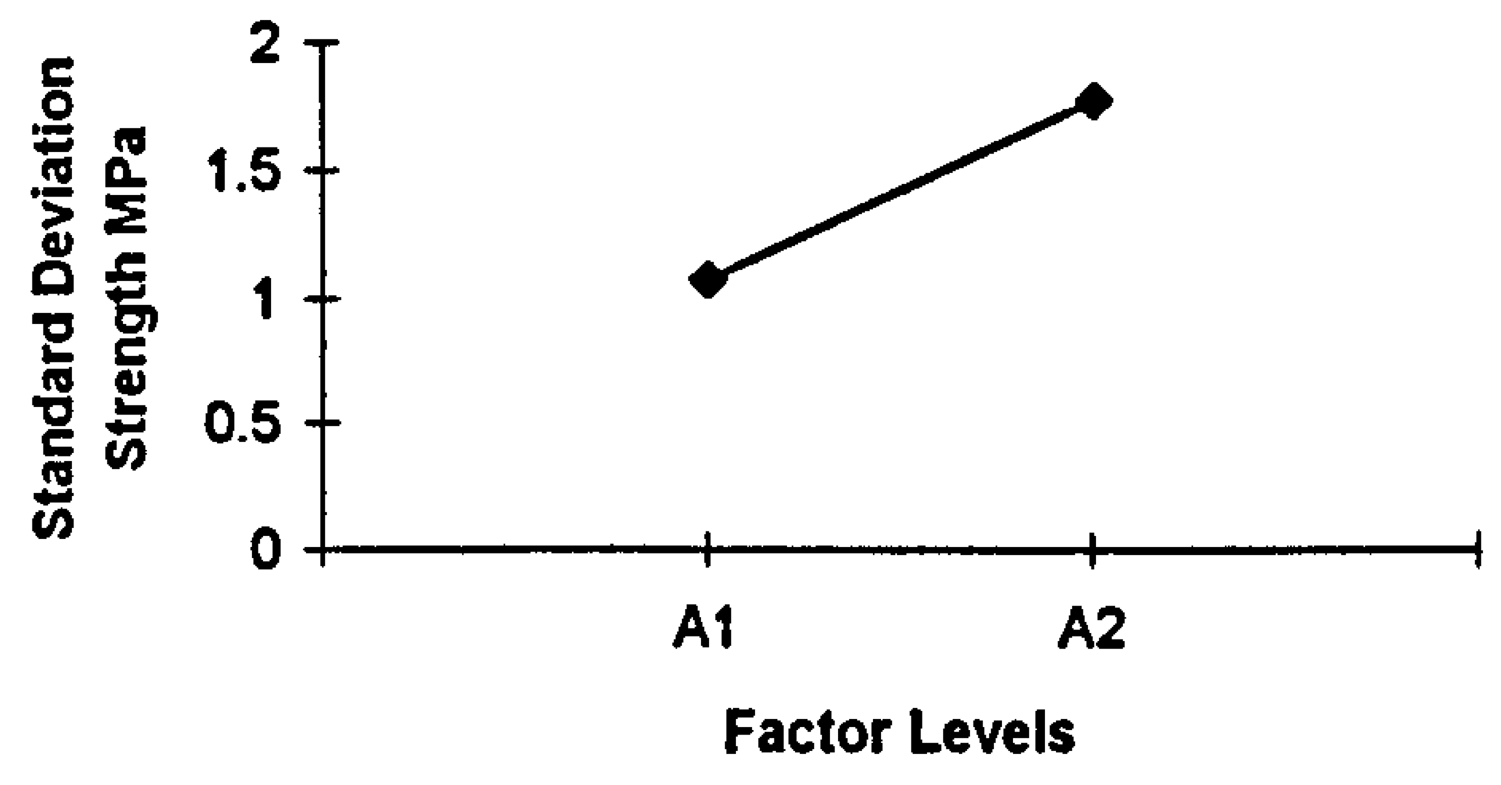


Figure 5.14 Main Effect of Factor A on ℓn(Standard Deviation) of Tensile Strength

5.7 Factors Affecting Mean and Standard Deviation of Thickness

A complete response data of the mean finger thickness is shown in Table 5.1. The analysis of variance for the finger thickness of the glove, is summarised in Table 5.10. The response variable is measured in millimetre (mm).

Table 5.10 reveals that factor D is statistically significant and has an F-value of 63.20 at ($p \leq 0.05$), while B has an F-value of 10.21 and statistically significant at ($p \leq 0.006$). Both factors exceed the critical F-value given in the F-Table. Since D has a larger F-value than B, we conclude that D has a larger effect on the response than factor B. The rest of the factors appear to have no statistically significant effect on the mean response. However, there is statistically significant difference between blocks. This implies that the blocking factor has an effect and was probably helpful in improving the precision of the comparison of means. It was also observed that interactions BE has quite high F-values and is statistically significant (at $p \leq 0.054$). Nevertheless, again it does make sense to suppose that this interaction has some impact on the mean thickness.

Table 5.10 Analysis of Variance for Mean Finger Thickness

Source of Variation	DF	Seq SS	Adj SS	Adj MS	F-value	P-value
A	1	0.000034	0.000034	0.000034	0.93	0.349
B	1	0.000367	0.000367	0.000367	10.21	0.006
C	1	0.000043	0.000043	0.000043	1.21	0.289
D	1	0.00227	0.00227	0.00227	63.20	0.000
E	1	0.000063	0.000063	0.000063	1.77	0.204
F	1	0.000011	0.000011	0.000011	0.28	0.604
G	1	0.000020	0.000020	0.000020	0.57	0.463
H	1	0.000014	0.000014	0.000014	0.40	0.538
AB=DF	1	0.000019	0.000019	0.000019	0.51	0.485
AE	1	0.000019	0.000019	0.000019	0.52	0.484
BD	1	0.000002	0.000002	0.000002	0.05	0.822
BE	1	0.000158	0.000158	0.000158	4.39	0.054
BF	1	0.000123	0.000123	0.000123	3.41	0.084
BG	1	0.000014	0.000014	0.000014	0.39	0.542
CD	1	0.000028	0.000028	0.000028	0.79	0.388
Block	1	0.006176	0.006176	0.006176	171.90	0.000
Error	15	0.000539	0.000539	0.000036		
Total	31	0.009899				

Note:Significance level ($p \leq 0.05$), DF= Degree of freedom, Seq ss= Sequential sum square, Adj ss= Adjusted sum square, Adj MS= Adjusted mean square

Next we investigate the adequacy of the model by graphing the residuals. The plot of residuals against fitted values, as shown in Figure 5.15 reveals that the points on this plot appears to be randomly scattered about the horizontal dashed line. In Figure 5.16 we plot standardised residuals against Normal scores. The residuals lie approximately along the dashed line with a few exceptions on the middle line. These plots show that the model assumptions are valid and any conclusion drawn is appropriate.

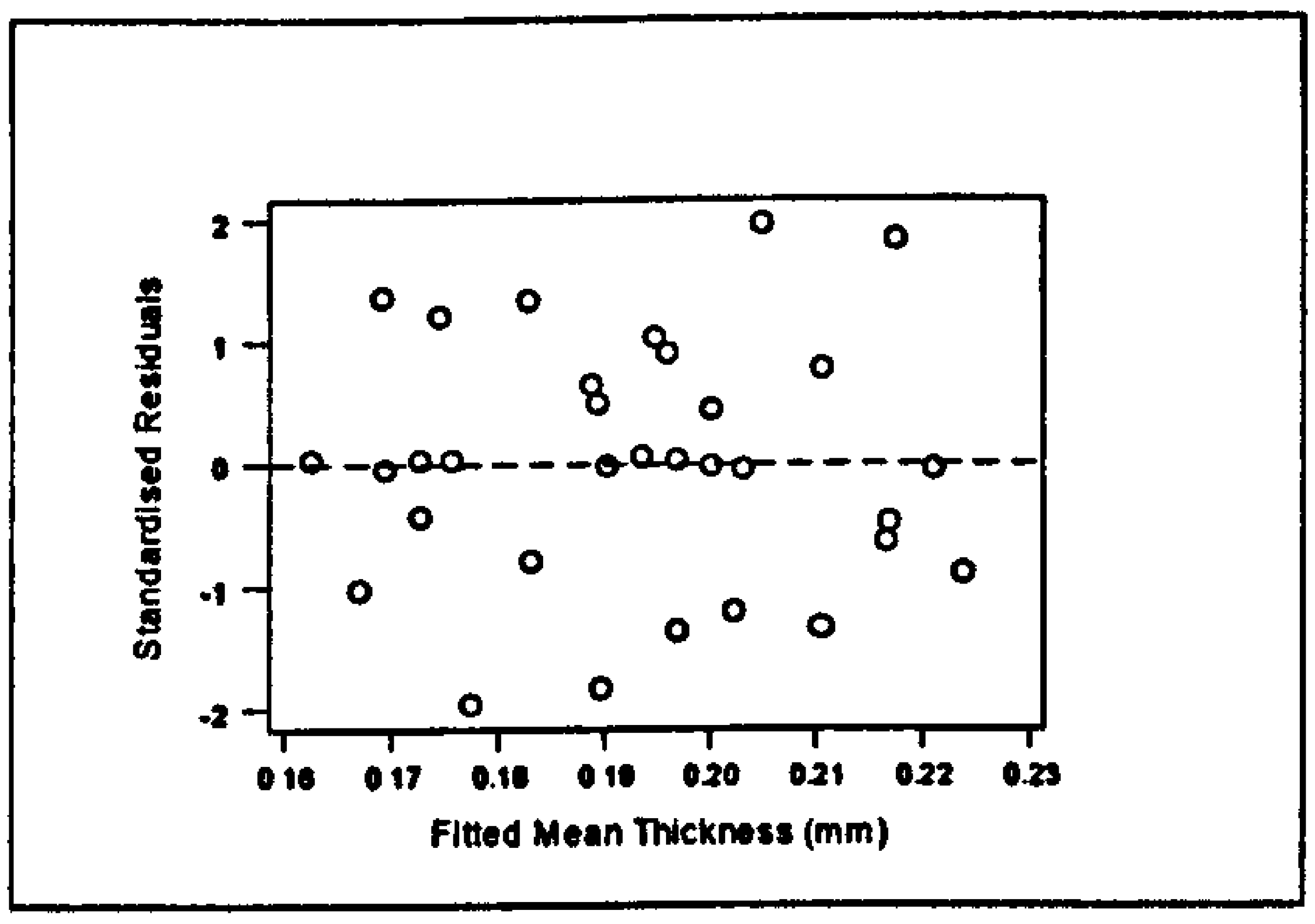


Figure 5.15 Residuals versus Fitted for Mean Thickness

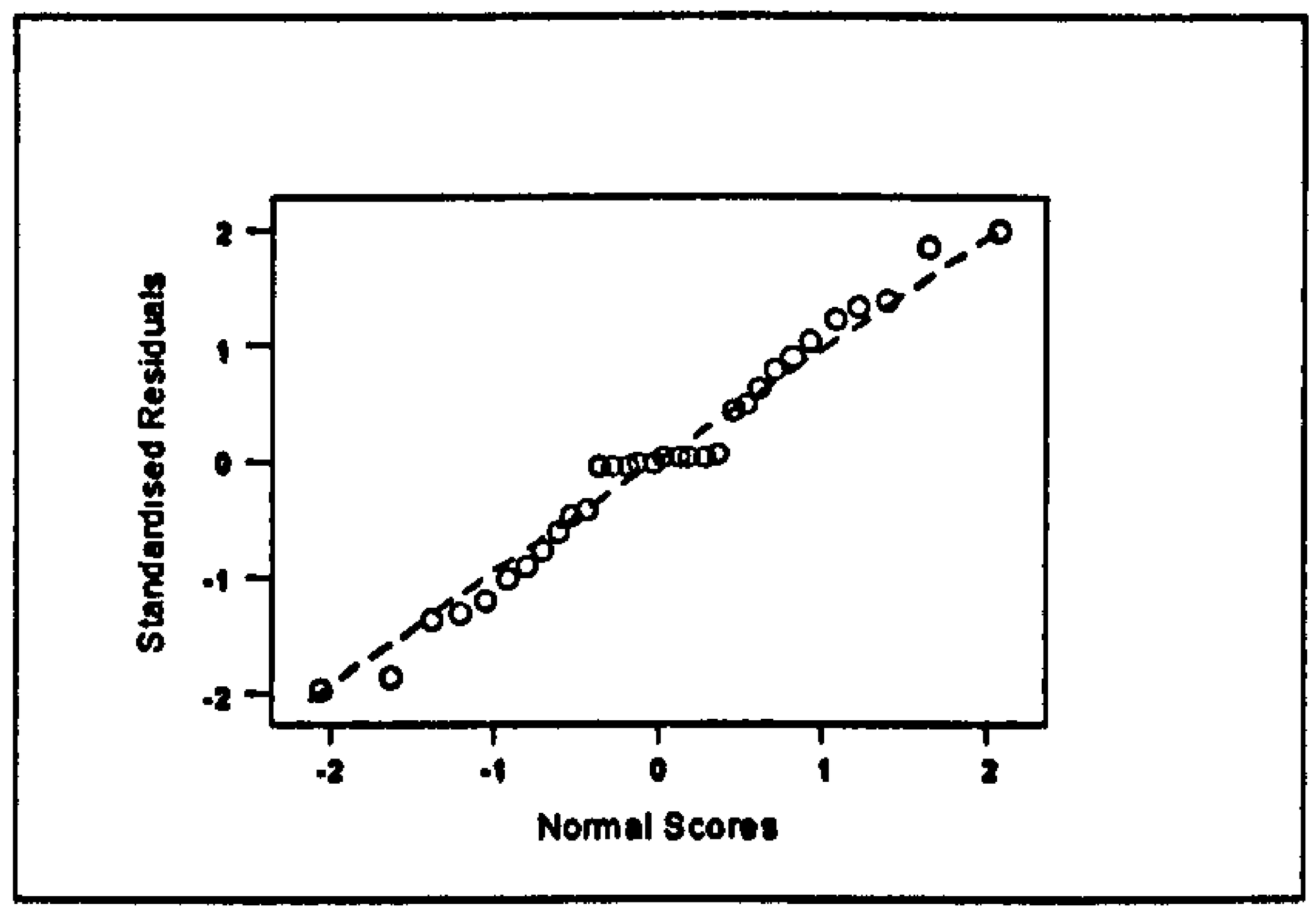


Figure 5.16 Residuals versus Nscores for Mean Thickness

Figure 5.17(a) presents the half-Normal probability plot of the effects estimate for the finger thickness. From examination of this plot it is clear that factors B, D and BE interaction are important contributors to finger thickness. We then removed the largest effect (D) to see if other effects are real. It is used to identify graphically the important effects, and determine whether any outliers are affecting the results. No effects stand out clearly on the plot except factors B and BE. The values needed to plot Figure 5.17 are shown in Appendix 4C.

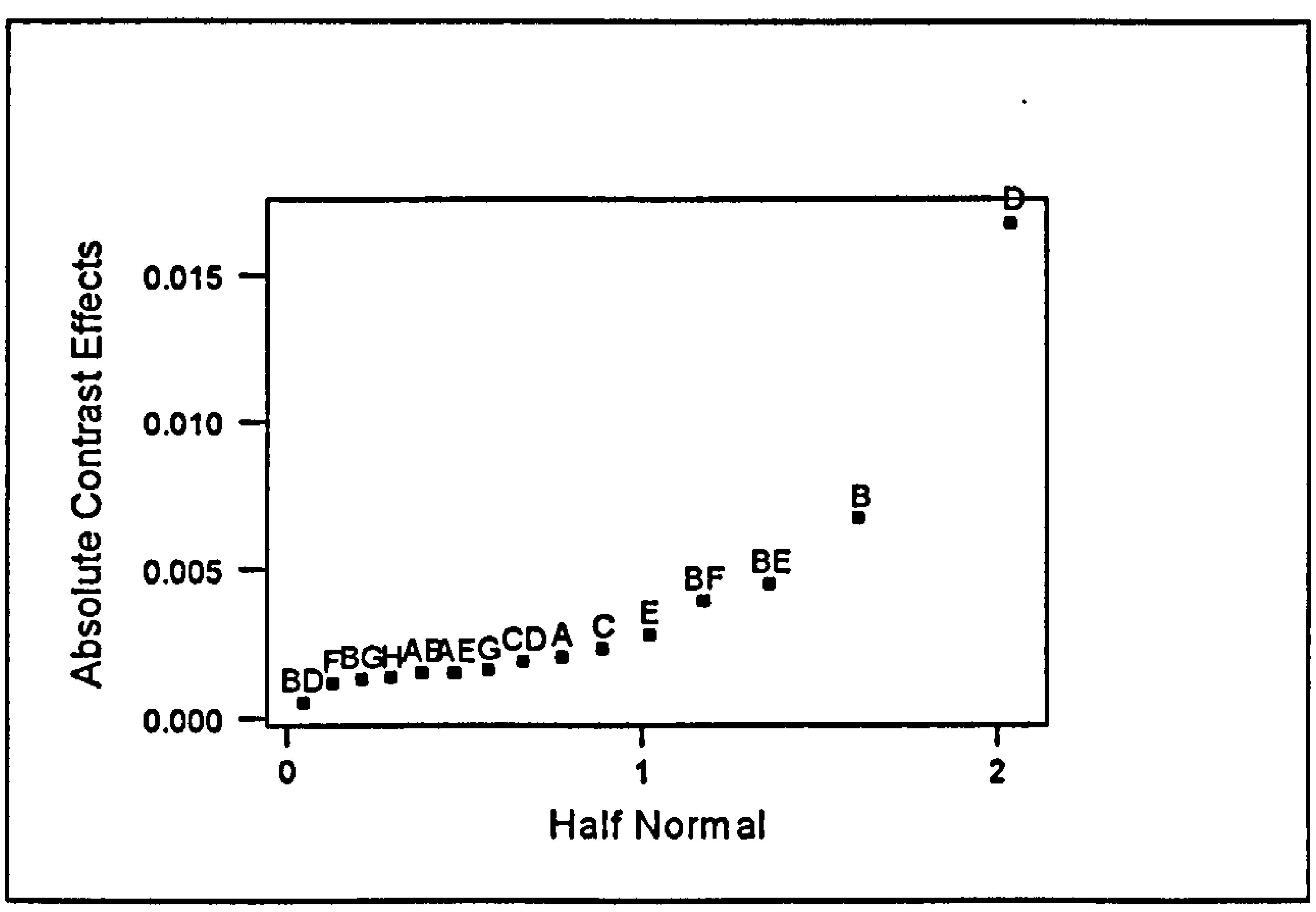


Figure 5.17(a) Half-Normal Probability Plot of Mean Thickness

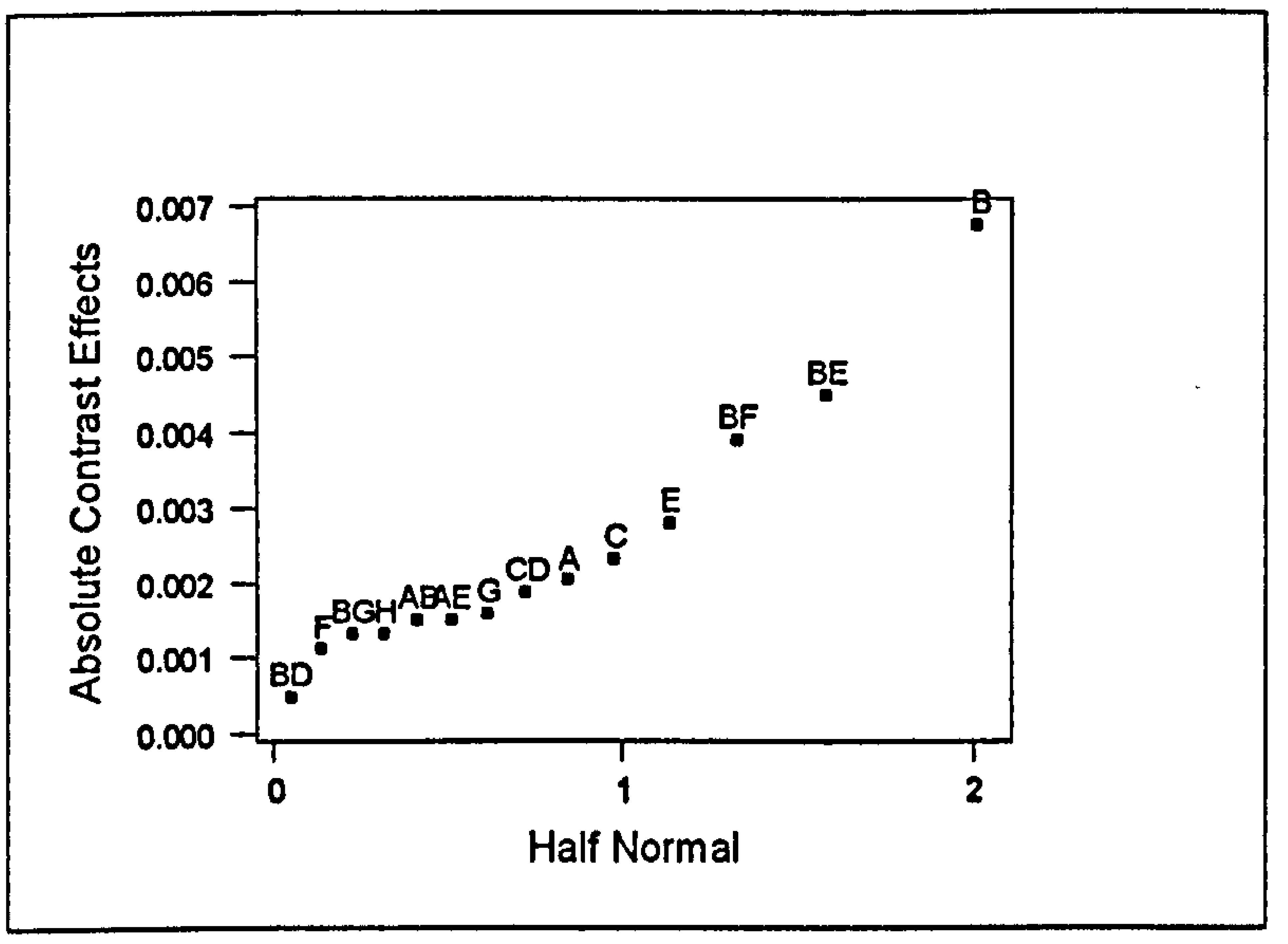


Figure 5.17(b) Half-Normal Probability Plot of Mean Thickness

Figure 5.17 Half-Normal Probability Plot of Thickness:(a) 15 contrasts;(b) 14 contrasts (D removed).

Once again we performed the 95% Confidence Intervals on the effects using equations 5.5 and 5.6 and the analysis is shown below. The analysis also indicates that D, B and BE are important factors as they are the only factor effect estimates for which the intervals do not include zero. Therefore, there is some evidence that these factors affect finger thickness.

Factor	95% Confidence Interval	Factor	95% Confidence Interval
BD	0.000484 ± 0.0045	A	0.002047 ± 0.0045
F	0.001122 ± 0.0045	C	0.002328 ± 0.0045
BG	0.001322 ± 0.0045	E	0.002816 ± 0.0045
H	0.001334 ± 0.0045	BF	0.003916 ± 0.0045
AB	0.001516 ± 0.0045	BE	0.004490 ± 0.0045
AE	0.001522 ± 0.0045	B	0.006772 ± 0.0045
G	0.001597 ± 0.0045	D	0.01685 ± 0.0045
CD	0.001890 ± 0.0045		

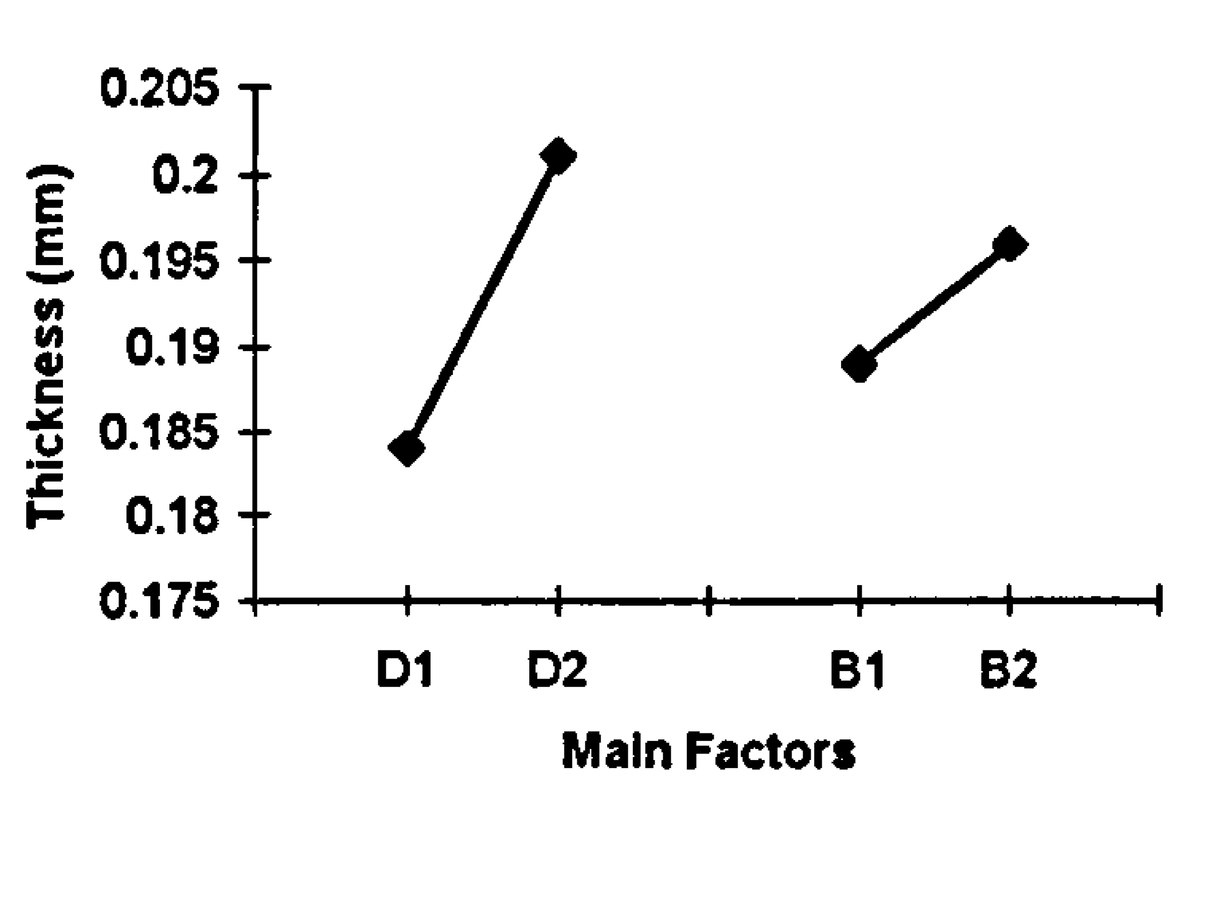
To assist in the interpretation of the results of the experiment as given in Table 5.10, a plot of the main effect is constructed as shown in Figure 5.18. The main effect plot is just a graph of the mean response at different levels of the factors as presented in Table 5.11. Figure 5.18 indicates that to get the average response as close as possible to the target value minimum specification limit of 0.18 mm, factors D and B should be set at the low level. For economical reasons factors A, C, F, G and H should be set at their low levels.

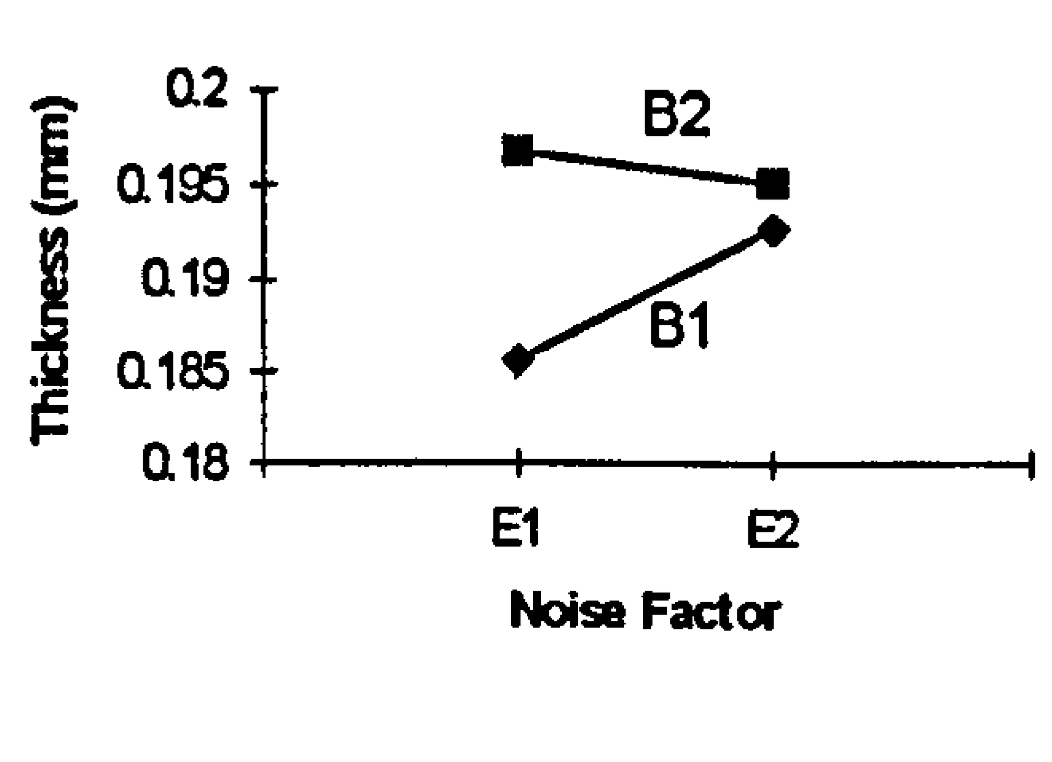
From the above analysis, there is some evidence that factors D and B are the important controllable factors that affect the mean of the finger thickness. The interaction BE also has an impact on the mean response. Since factors B and E are involved in the interaction, it is necessary to examine the BE interaction plot before determining the appropriate levels.

Table 5.11 Main Effects of Factors B and D on Mean Thickness

Levels	Factors	
	B(mm)	D(mm)
Average Response at High Level (2)	0.196	0.201
Average Response at Low level (1)	0.189	0.184
Main Effect	0.007	0.017

The estimated effects for interaction of BE as shown in Table 5.19 is statistically significant. These estimated effects are plotted in Figures 5.18 to confirm interaction effect. Since factor E is humidity we could not control the levels. We then used factor B for adjustment. We noted that when factor E (humidity) is high, it has almost no effect on the mean response regardless of the levels of factor B. But if E is low, the glove thickness varies when factor B changes. Setting B at high yields thicker gloves and has smaller slope than when it is set low as depicted in Figure 5.19. Moreover, at this level, the effect of humidity on the process is minimised. The BE interaction suggests that there is an opportunity to reduce the effect of humidity on factor B and therefore the process will be robust against noise.





Fgure 5.18 Main Effects Thickness Figure 5.19 Interaction Effects on Thickness

E_1(Low)	E_2(High)	
0.186 mm	0.193 mm	B_1(Low)
0.197 mm	0.195 mm	B_2(High)

Table 5.12 Interaction Effect of BE on Mean Thickness

We then analysed the standard deviation data of the finger thickness as presented in Table 5. 2. The results from the ANOVA is given in Table 5.13. The F-test revealed that none of the factors affects the standard deviation response. There is some indication that these factors do not influence process variability. Factors A, C, F, G, and H are inactive. This means that they can be adjusted to any level without effecting either the process mean or process variability. Therefore, these factors should be set at a level to optimise cost. Although factors D and B did not have effect on the process variability, they did affect the process mean. We would then focus on trying to control factors D and B.

Table 5.13 Analysis of Variance for ℓn(Standard Deviation) on Finger Thickness

Source of variation	DF	Seq SS	Adj SS	Adj MS	F-value	P-value
A	1	0.0081	0.0081	0.0081	0.07	0.800
B	1	0.2952	0.2952	0.2952	2.44	0.139
C	1	0.0055	0.0055	0.0055	0.05	0.834
D	1	0.0002	0.0002	0.0002	0.00	0.971
E	1	0.2629	0.2629	0.2629	2.17	0.161
F	1	0.0047	0.0047	0.0047	0.04	0.847
G	1	0.0454	0.0454	0.0454	0.37	0.550
H	1	0.0625	0.0625	0.0625	0.52	0.484
AB=DF	1	0.0234	0.0234	0.0234	0.19	0.667
AE	1	0.0054	0.0054	0.0054	0.04	0.836
BD	1	0.0140	0.0140	0.0140	0.12	0.739
BE	1	0.0872	0.0872	0.0872	0.72	0.410
BF	1	0.0981	0.0981	0.0981	0.81	0.382
BG	1	0.1129	0.1129	0.1129	0.93	0.350
CD	1	0.0537	0.0537	0.0537	0.44	0.516
Block	1	0.1979	0.1979	0.1979	1.63	0.221
Error	15	1.8166	1.8166	0.1211		
Total	31	3.0935				

Note: Significance level ($p \leq 0.05$), DF= Degree of freedom, Seq ss= Sequential sum square, Adj ss= Adjusted sum square, Adj MS= Adjusted mean square

The analysis on 95% Confidence Intervals are performed to confirm the important factors. Since all these factors include zero in the intervals, there is some evidence that none of these factors is important.

Factor	95% Confidence Intervals	Factor	95% Confidence Intervals
D	0.0046 ± 0.2621	CD	0.0818 ± 0.2621
AE	0.0242 ± 0.2621	H	0.0884 ± 0.2621
F	0.0260 ± 0.2621	BE	0.1044 ± 0.2621
C	0.0262 ± 0.2621	BF	0.1107 ± 0.2621
A	0.0317 ± 0.2621	BG	0.1188 ± 0.2621
BD	0.0418 ± 0.2621	E	0.1813 ± 0.2621
DF	0.0541 ± 0.2621	B	0.1921 ± 0.2621
G	0.0751 ± 0.2621		

5.8 Factors affecting Mean and Standard Deviation of Weight

Weight is also one of the quality characteristics that we are interested in. The response variable is measured in gram (gm). Again a complete results of this experiment is shown in Table 5.1. The analysis of variance is summarised in Table 5.14. The results showed that the latex temperature (B), percent of calcium nitrate(D), percent of calcium carbonate (F), and the DF interaction are statistically significant. Factor D appears to have the largest effect followed by factor B and next interaction DF and factor F. The effects of D, B, F and interaction DF estimated in this analysis are location effects. This suggests that changing these factor levels will change the average effect of the mean response variable. Factors A, C, E, G and H which are considered in the experiment are not statistically significant. This means they do not influence the mean weight of the gloves.

Table 5.14 Analysis of Variance for Mean Weight

Source of variation	DF	Seq SS	Adj SS	Adj MS	F-value	p-value
A	1	0.0166	0.0166	0.0166	0.74	0.402
B	1	0.2403	0.2403	0.2403	10.75	0.005
C	1	0.0058	0.0058	0.0058	0.26	0.618
D	1	3.1658	3.1658	3.1658	141.61	0.000
E	1	0.0115	0.0115	0.0115	0.52	0.484
F	1	0.1055	0.1055	0.1055	4.72	0.046
G	1	0.0004	0.0004	0.0004	0.02	0.895
H	1	0.0284	0.0284	0.0284	1.27	0.278
AB(=DF)	1	0.1103	0.1103	0.1103	4.94	0.042
AE	1	0.0045	0.0045	0.0045	0.20	0.659
BD	1	0.0316	0.03156	0.0316	1.41	0.253
BE	1	0.0001	0.0001	0.0001	0.00	0.955
BF	1	0.0012	0.0012	0.00121	0.05	0.819
BG	1	0.0088	0.0088	0.0088	0.39	0.541
CD	1	0.0005	0.0005	0.0005	0.02	0.879
Block	1	0.0254	0.0254	0.0254	1.13	0.304
Error	15	0.3353	0.3353	0.0224		
Total	31	4.09193				

Note:Significance level ($p \leq 0.05$), DF= Degree of freedom, Seq ss= Sequential sum square, Adj ss= Adjusted sum square, Adj MS= Adjusted mean square

Model adequacy, was checked by looking at the residuals of the experimental results. The residual analysis of this data is given in Figure 5.20 and 5.21. Examination of the plot reveals that the residuals are slightly clustered but will not affect the F-value significantly, since the F-test is quite robust as discussed earlier in p.71. The Normal scores plot Figure 5.21, is roughly linear. Therefore the model assumptions hold true.

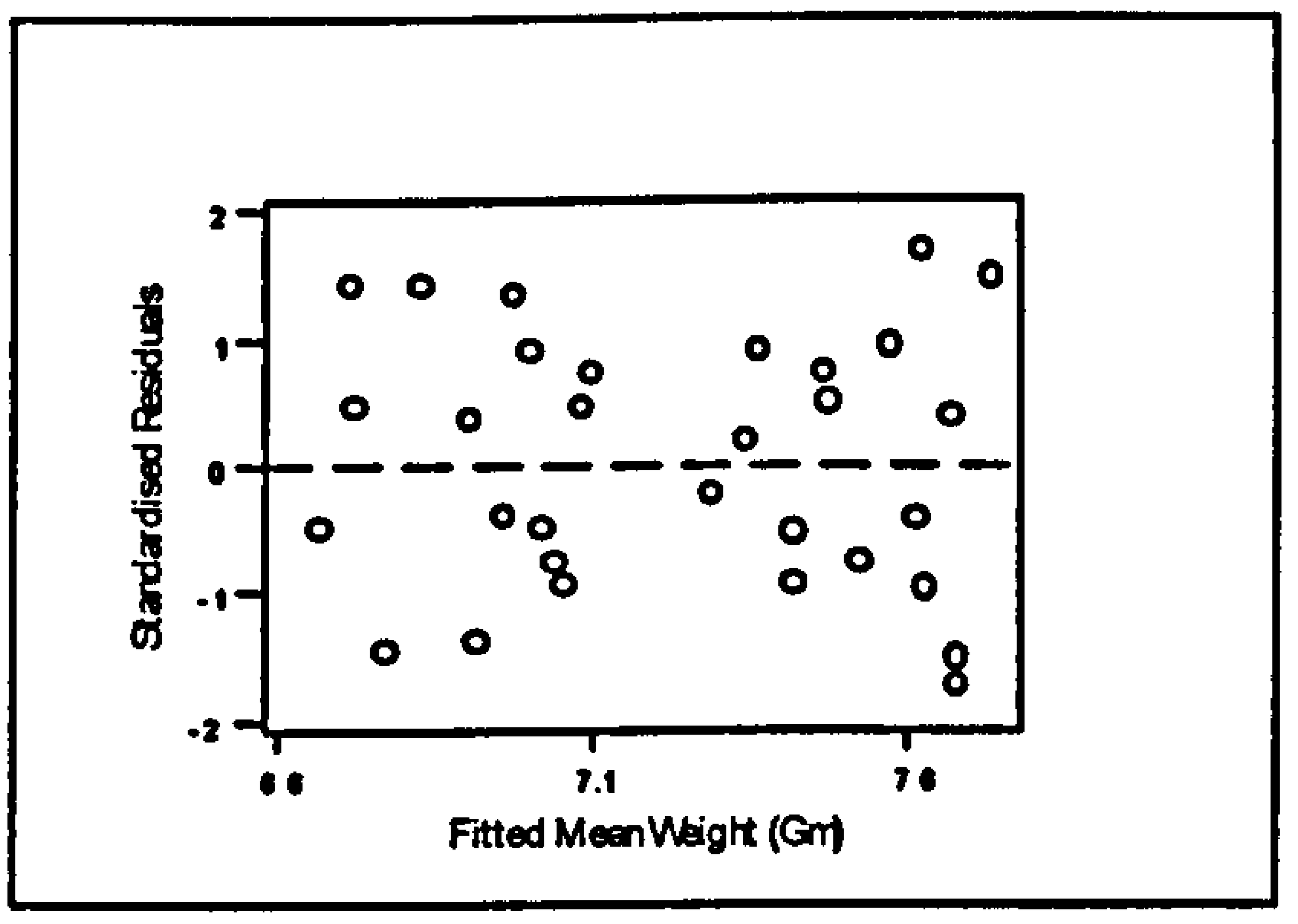


Figure 5.20 Residual versus Fitted for Weight

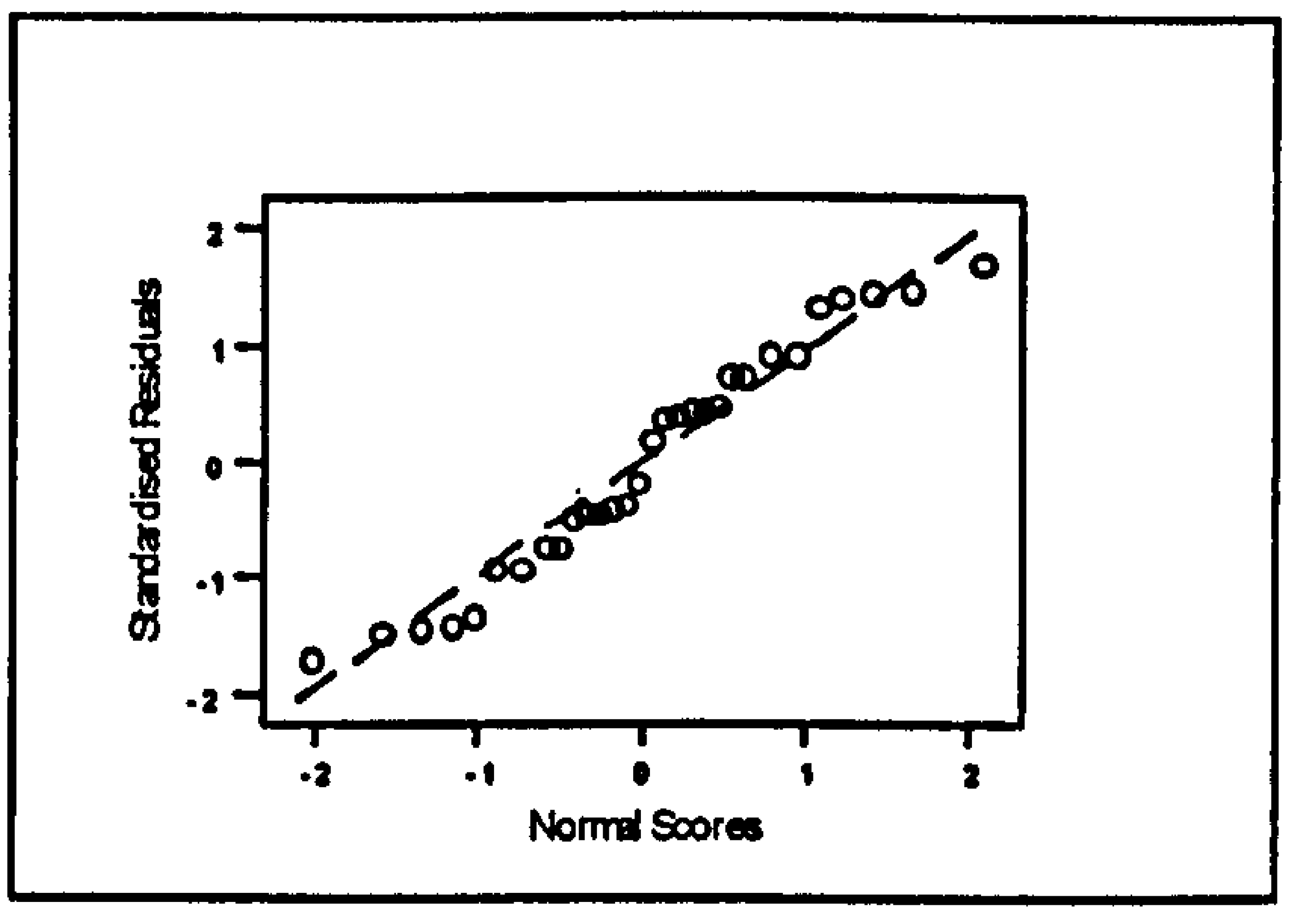


Figure 5.21 Residuals versus NScores for Weight

The half-Normal probability plot is presented in Figure 5.22. The point D stand out clearly on the plot as it is some what separated from the others. We then removed the largest effect which was D and re-plot the remainder effects as shown in Figure 5.22(b). The plot suggests that B, F and DF interaction are important factors affecting the weight of the glove. This finding agrees very well with the ANOVA Table 5.14. The values needed to plot this diagram is given in Appendix 4D. The finding shows that factors B, D, F and interaction DF are the only important factors that affect the mean response of the weight.

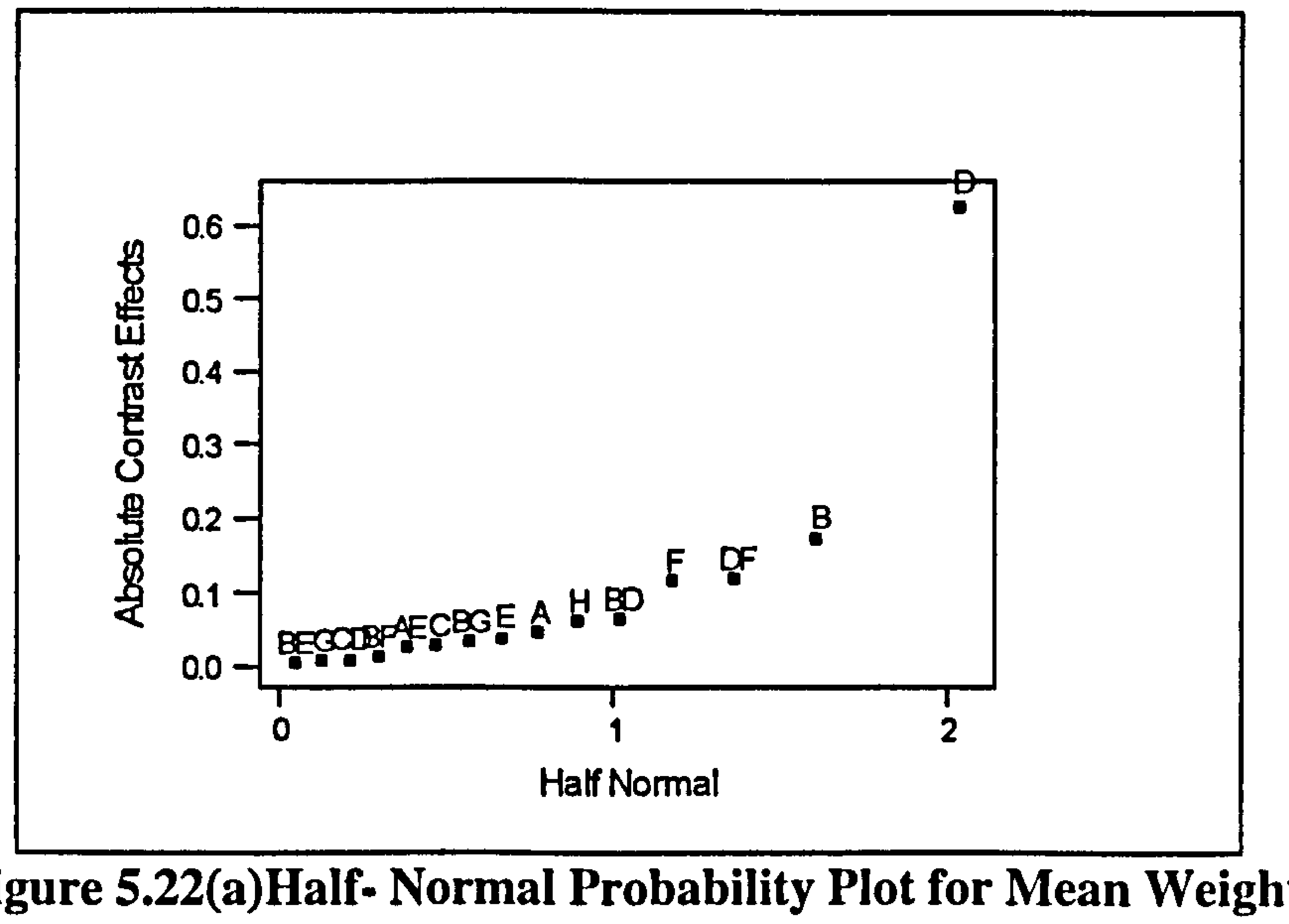


Figure 5.22(a)Half- Normal Probability Plot for Mean Weight

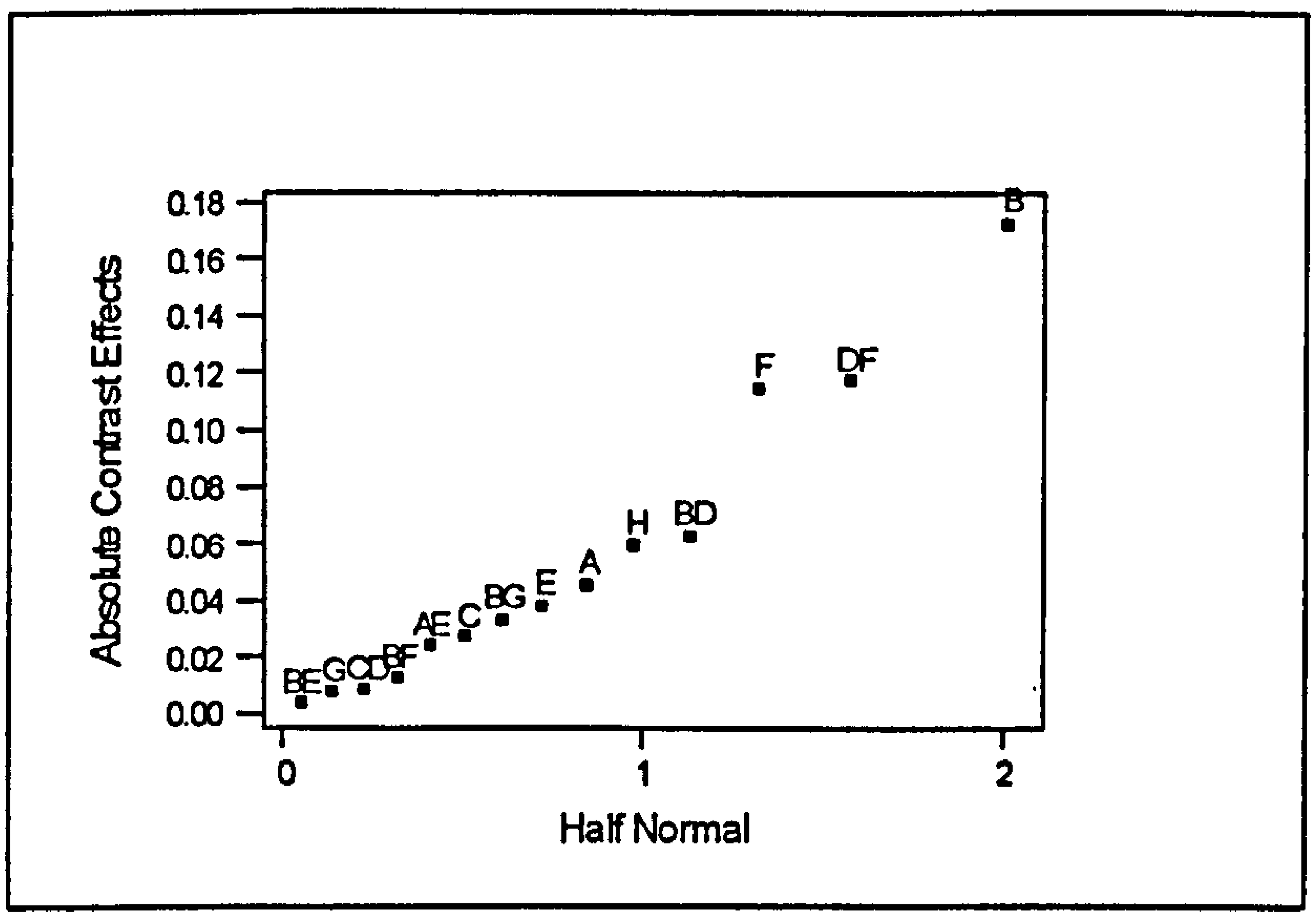


Figure 5.22(a)Half- Normal Probability Plot for Mean Weight

Next we also calculate the standard error of the effects and compare the magnitude of the effects to their standard errors. The variance estimate given by the error mean square in the analysis of variance ANOVA is substituted in equations 5.5 and 5.6. Thus at 95% confidence intervals, the analysis revealed the following:-

Factor	95% Confidence Intervals	Factor	95% Confidence Intervals
BE	0.0031 ± 0.0927	A	0.0456 ± 0.0927
G	0.0071 ± 0.0927	H	0.0596 ± 0.0927
CD	0.0082 ± 0.0927	BD	0.0628 ± 0.0927
BF	0.0123 ± 0.0927	F	0.1148 ± 0.0927
AE	0.0238 ± 0.0927	DF	0.1174 ± 0.0927
C	0.0269 ± 0.0927	B	0.1733 ± 0.0927
BG	0.0331 ± 0.0927	D	0.6291 ± 0.0927
E	0.0379 ± 0.0927		

The most important factors are D, B, DF, and F, as they are the only factor effect estimates for which the intervals do not include zero.This results confirm that there is some evidence that these factors influence the mean weight of gloves.

A follow-up analysis was performed, in order to interpret the results and also to explore further the interaction between factors D and F. Figure 5.23 was constructed based on Table 5.15 at each factor level for the main effects, temperature of latex (B), percent of calcium carbonate (F), and percent of calcium nitrate (D). The results of the analysis give us the following setting level, $B_2D_2F_2$ to maximise glove weight. We are tempted to interpret the main effects separately which in this case could be quite misleading. This is because the DF interaction is significant. The average response should therefore be estimated at each combination of D and F levels. But the DF interaction has confounded effects, which means we are not able to assess which of the four effects may be affecting the glove weight. DF is aliased to AB, CE, and GH, (AB=DF=CE=GH). However none of the main factors of the interactions CE and GH are significant, hence their effects are insignificant. On the other hand, the DF interaction effect is significant as their main factors are significant. Nevertheless based on our process knowledge of the experimental factors, factors A and B cannot interact. This leaves interaction effect DF. This conclusion is supported by the high F-value for both D and F as shown in Table 5.14.

Table 5.15 Estimated Effects of Factors D, B and F on Mean Weight

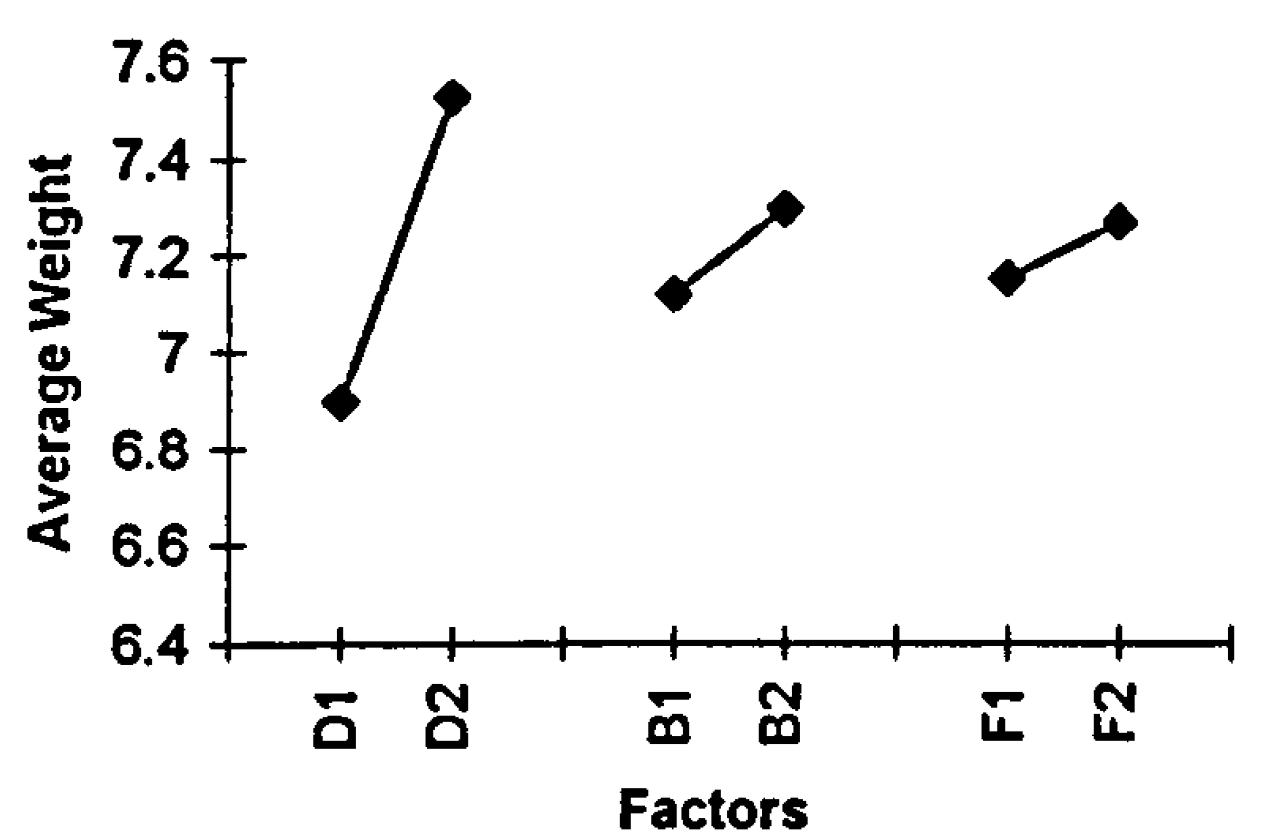
Levels	Factors		
	D (gm)	B (gm)	F(gm)
Average Response at Low Level (1)	6.895	7.122	7.150
Average Response at High Level (2)	7.524	7.296	7.266
Main Effect	0.629	0.173	0.115

The interaction of DF is presented graphically in Figure 5.24. The values needed to plot this diagram are given in Table 5.15. The lack of parallelism indicates the presence of interaction effect between the two factors. Thus if we want to determine what factor levels produce the largest average value for the weight of glove, we look for the combination of factors D and F that produces the largest average weight. Changing D (percent of calcium nitrate) from low to high, increases the weight of the glove whether calcium carbonate is set at high or low. Due to economical reason, therefore, factor F at low was chosen. On the other hand interactions between factors B and D and factors B and F are not significant at ($p \leq 0.05$). We could thus select the best value for B without regard to factor D or F. In this case the best choice is B at its high level.

F_1 (Low)	F_2 (High)	
6.79 gm	7.01 gm	D_1(Low)
7.53 gm	7.52 gm	D_2(High)

Table 5.16 Interaction Effects of DF on Weight

The analysis shows that the main factors D_2,B_2,F_2 and D_2F_2 interaction are the most important effects on the weight of the gloves. In this situation both the main effect of a factor and the interaction effect are significant. The choice has to be made on the basis of the interaction, since this is telling us that although one factor level appears to give better results on average, another level will produce even greater benefits when used in conjunction with a particular level of the other factor as illustrated in Figure 5.24. Therefore D_2F_2 interaction is chosen and this combination is similar as the main factors.



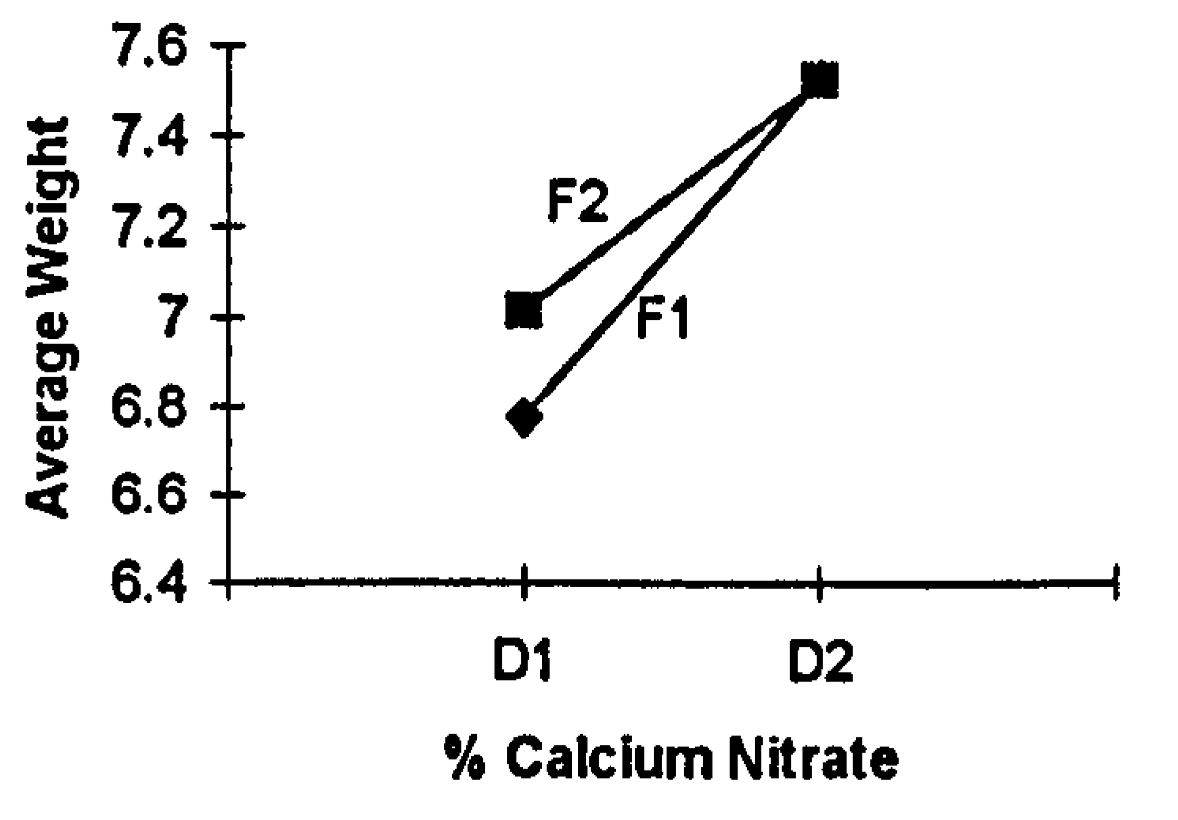


Figure 5.23 Main Effects for Weight **Figure 5.24 Interaction Effects for Weight**

We have also performed an analysis of variance for the standard deviation of the weight. An analysis of variance is presented in Table 5.17. The analysis showed that factor H (pH of latex) was found to be statistically significant (at $p \leq 0.01$) with an F-value of 9.10. The next largest influence is factor D (percent calcium nitrate) with an F-value of 6.21 and statistically significant (at $p \leq 0.02$). Hence there is some evidence that factors D and H influence the process variability.

Model adequacy checks were conducted. The plot of residuals against fitted values in Figure 5.25 showed that the points are clustered in the middle. This could influence the F-value slightly, however F-test is robust as discussed in p.71. The Normal scores plot of the residuals indicates that they fall roughly on the dashed line with the exception of a few points.

Table 5.17 Analysis of Variance on ℓn(Standard Deviation) of Weight

Source of variation	DF	Seq SS	Adj SS	Adj MS	F-value	p-value
A	1	0.02492	0.02492	0.024925	0.68	0.423
B	1	0.00213	0.00213	0.002130	0.06	0.813
C	1	0.00894	0.00894	0.00894	0.24	0.629
D	1	0.22811	0.22811	0.22811	6.21	0.025
E	1	0.02456	0.02456	0.024563.	0.67	0.426
F	1	0.03462	0.03462	0.03462	0.94	0.347
G	1	0.03416	0.03416	0.03416	0.93	0.350
H	1	0.33441	0.33441	0.33441	9.10	0.009
AB(=DF)	1	0.01444	0.01444	0.01444	0.39	0.540
AE	1	0.02388	0.02388	0.02388	0.65	0.433
BD	1	0.10102	0.10102	0.10102	2.75	0.118
BE	1	0.00601	0.00601	0.00601	0.16	0.691
BF	1	0.08266	0.08266	0.08266	2.25	0.154
BG	1	0.05997	0.05997	0.05997	1.63	0.221
CD	1	0.01754	0.01754	0.01754	0.48	0.50
Block	1	0.01939	0.01939	0.01939	0.53	0.479
Error	15	0.55095	0.55095	0.03673		
Total	31	1.56773				

Note: Significance level ($p \leq 0.05$), DF= Degree of freedom, Seq ss= Sequential sum square, Adj ss= Adjusted sum square, Adj MS= Adjusted mean square

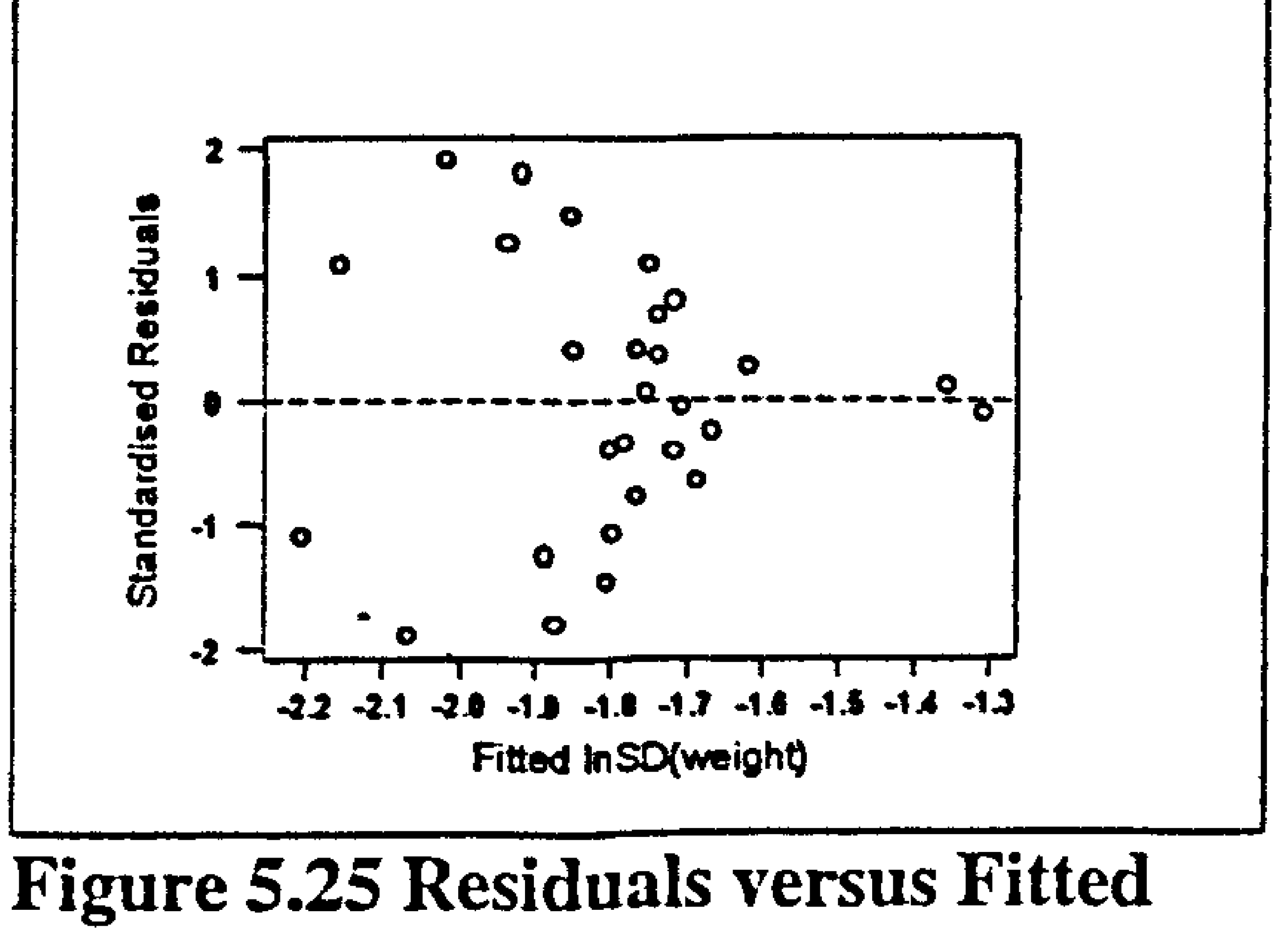


Figure 5.25 Residuals versus Fitted of ℓn(SD)Weight

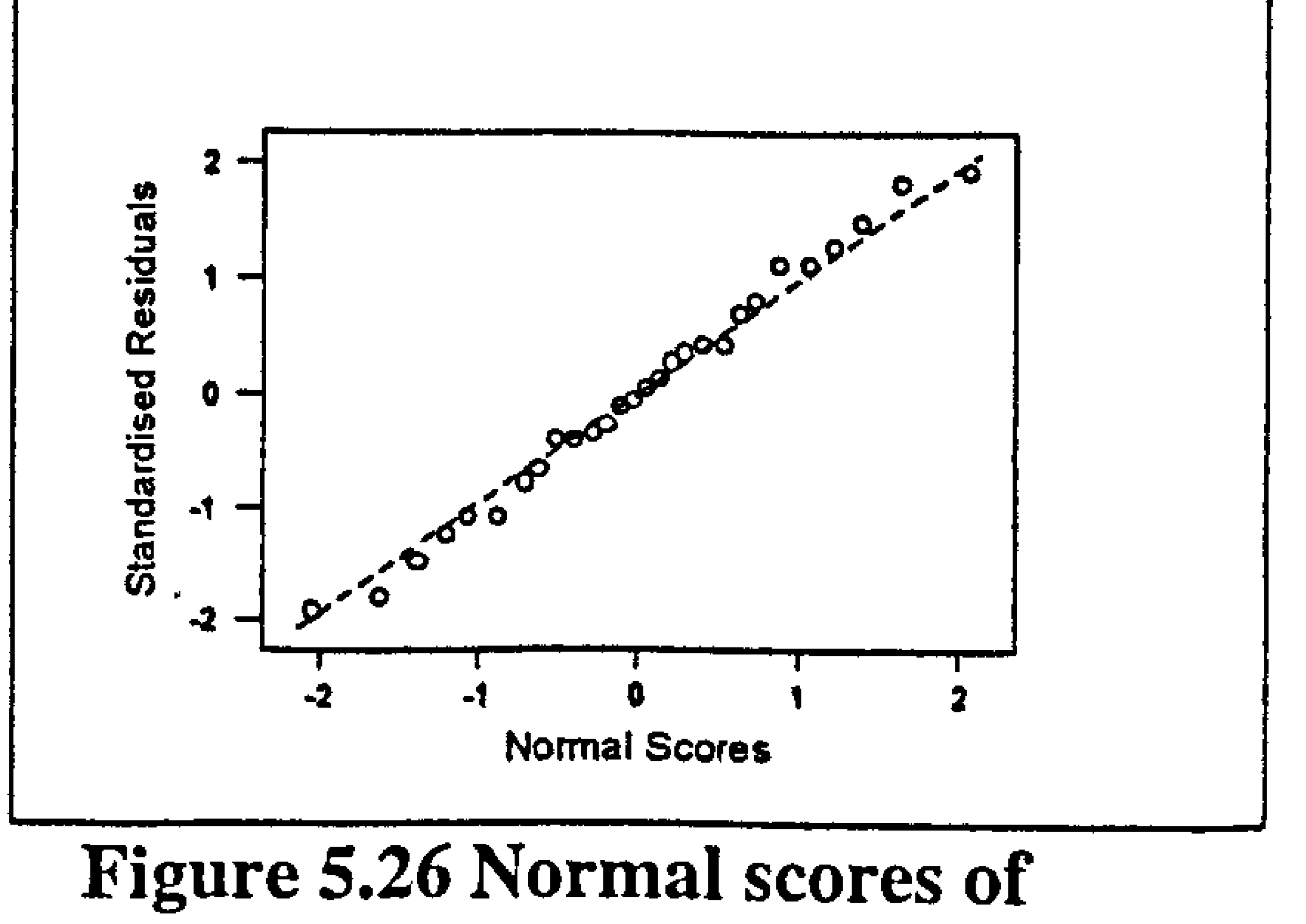


Figure 5.26 Normal scores of ℓn(SD)Weight

Figure 5.27 presents a half-Normal probability plot of the factor effects estimate for the standard deviation weight of the gloves. From examination of this plot it is clear that factors H and D are strong contributors to process variability.

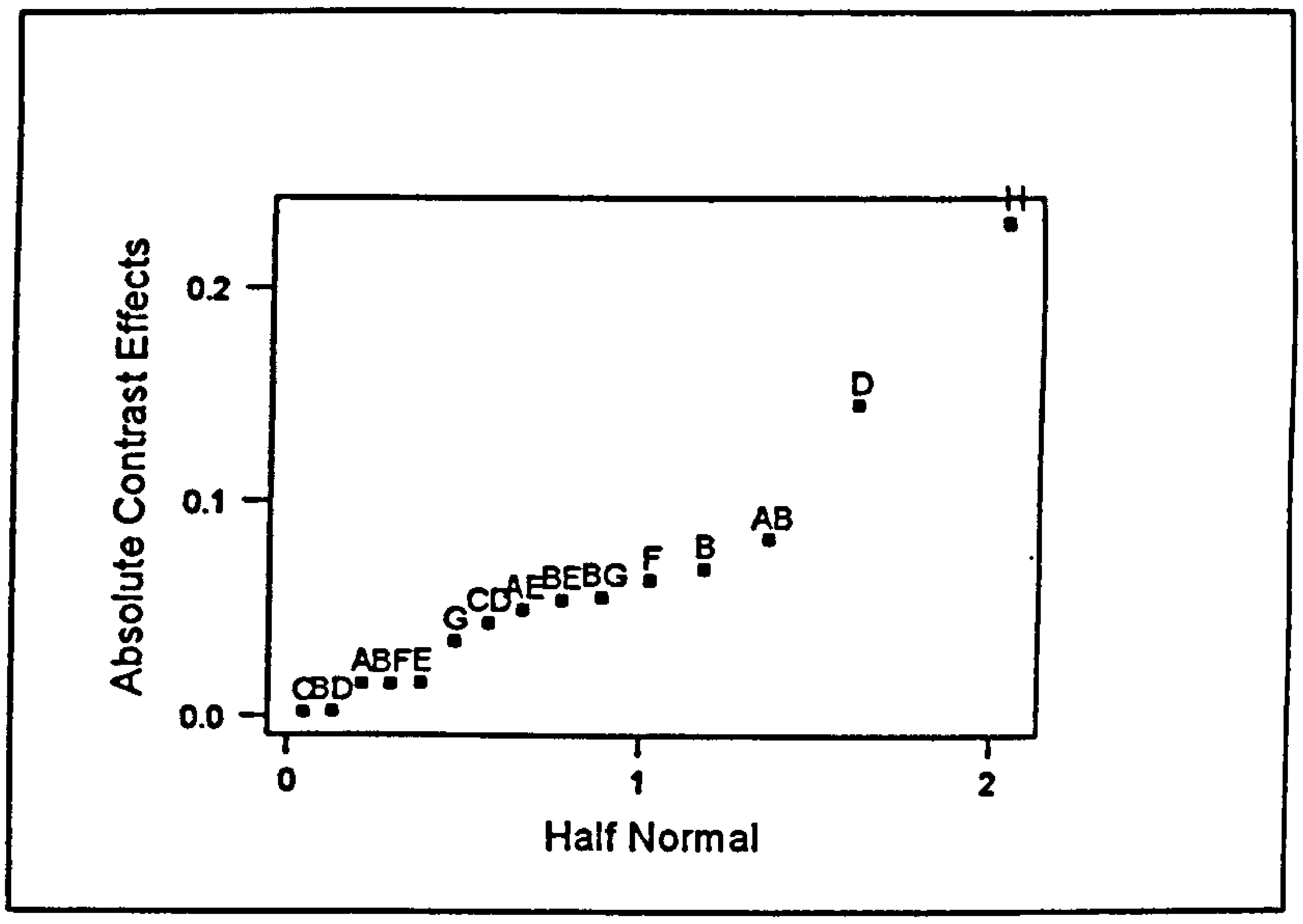


Figure 5.26 Half- Normal Probability Plot for ℓn(Standard deviation) Weight

Once again, we performed the 95% confidence intervals on the dispersion effect using equations 5.5 and 5.6 and the analysis is shown below. Since only factors H and D excluded zero in the intervals, there is some evidence that they influenced the process variability.

Factor	95% Confidence Interval	Factor	95% Confidence Interval
C	0.00176 ± 0.1443	BE	0.0546 ± 0.1443
BD	0.0029 ± 0.1443	BG	0.0558 ± 0.1443
A	0.0156 ± 0.1443	F	0.0643 ± 0.1443
BF	0.0158 ± 0.1443	B	0.0694 ± 0.1443
E	0.0160 ± 0.1443	AB	0.0832 ± 0.1443
G	0.0355 ± 0.1443	D	0.1461 ± 0.1443
CD	0.0440 ± 0.1443	H	0.2312 ± 0.1443
AE	0.0501 ± 0.1443		

We did a follow-up analysis for both factors H (pH of latex) and D (percent calcium Nitrate). Their effects at different levels were estimated and presented in Figure 5.28. It suggested that if H is set low the standard deviation will increase and vice versa. Similarly, factor D if set high will increase the process variability.

From this analysis we noted that factor H does not affect the mean weight, but it does affect the standard deviation in the process. While factor D affects both the mean and the standard deviation in the process. Hence, to reduce process variability around the glove mean weight, set factor H high and factor D low. Coupling the information about the mean and standard deviation of the process, the preferred setting would be $A_1B_2C_1D_1F_2G_1H_2$ so as to minimise variation in the process and product.

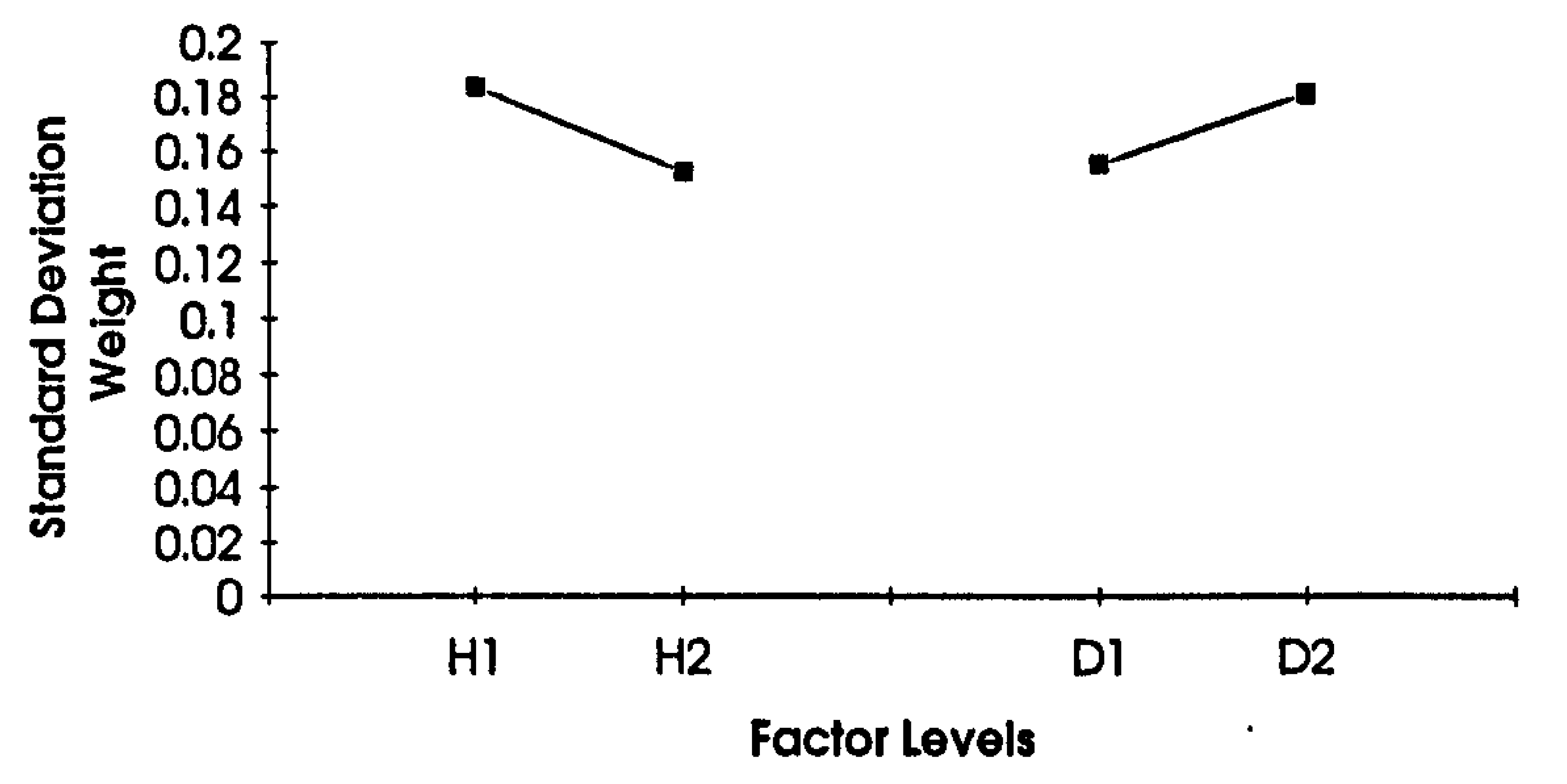


Figure 5.28 Main Effects on ℓn(SD) Weight

5.9 Chapter Summary

The optimal level settings for the rubber glove with multiple characteristics were determined using the standard analysis of variance and the F-test. The primary objective of the robust process design is to choose the best level settings of the control factors that will maximise the mean and minimise the variation in the glove's quality characteristics at minimum cost. The quality characteristics of the glove that were considered in this study were the pinhole, the tensile strength, the finger thickness and the weight. Analysis of variance and half-Normal probability plots were used in the analysis. The findings are summarised in Table 5.18.

Table 5.18 Selected Optimum Settings

Quality Characteristics	Factors Levels
Square root Pinholes (%)	$A_1B_1C_1D_1F_1G_2H_1$
Tensile Strength (MPa)	$A_1B_1C_1D_1F_1G_1H_1$
Logarithm (thickness) (mm)	$A_1B_2C_1D_1F_1G_1H_1$
Weight (gm)	$A_1B_2C_1D_1F_2G_1H_2$

These investigations showed that the pinholes response was significantly affected by oven temperature after coagulant dip (G) and latex temperature (B). It showed that factor G appears to be the biggest single effect followed by an interaction between latex temperature (B) and humidity (E). Other factors which appear insignificant are not important and could be set at low levels for economical reasons. The BE interaction suggests that factor B is sensitive to humidity. The best level setting for pinhole was $A_1B_1C_1D_1F_1G_2H_1$

As far as the tensile strength of the glove is concerned, the results suggested that the oven temperature after coagulant dip (G), curing temperature profile (A) and BG interaction have significant effect on the average strength. It appears that factor G has the largest influence, followed by factor A. Factors B, C, D, F and H appear to have no effect on the mean strength of the glove, hence they should be set at their low levels since these are the least expensive levels. The presence of B_1G_1 interaction enhances the mean strength when both factors are set at low. There is some evidence that the standard deviation response will increase if factor A is high. Factor A appears to affect both the mean and process variability. This suggests that factor A cannot be used as an adjusted factor. Hence to reduce process variability factor A should be set at low level. We conclude that the preferred settings are $A_1B_1C_1D_1F_1G_1H_1$.

The other quality characteristic that was considered in the study was finger thickness. The results revealed that the largest effect on the mean response was the percent of calcium nitrate (D), and latex temperature(B). Both factors when set at the high level increase the gloves' thickness. The interaction between B_2F_2 suggests that the thickness was particularly enhanced if both are set at high. The interaction at BE suggests that factor B_2 is robust to humidity. None of the controllable factors appear to have any effect on the standard deviation response. The optimal setting for finger thickness is at $A_1B_2C_1D_1F_1G_1H_1$.

For the weight data, it was found that the percent of calcium nitrate (D), latex temperature (B) and percent of calcium carbonate (F) affect the average weight of the glove. Factor D has the largest effect on the mean weight. The DF interaction suggests that the mean weight could be maximised when factors D and F are high. However factor D at high level and factor H at low would increase the standard deviation response. Hence to reduce variation around the mean weight, factor D and H are set at low and high levels respectively. Thus the best setting chosen for the mean weight is $A_1B_2C_1D_1F_2G_1H_2$.

An important finding that emerged from this analysis is the interaction between control factor and noise factor. This allows us to identify control factors which minimise the effect of noise. Mean analysis shows that there is strong interaction between the latex temperature (B) and humidity (E) for the pinholes and finger thickness. Thus, it would appear that the latex temperature (B) is sensitive to humidity as far as pinholes and thickness responses are concerned. Therefore factor B could be made robust to humidity variation. Formers' temperature (C) was found to have no effect on either the mean or the standard deviation for all the quality characteristics considered in the experiment. This indicates that factor C does not have to be controlled tightly. We discovered that factor G has the largest effect on both the pinholes and tensile strength of the gloves. While factor D has the largest influence on both the weight and finger thickness of the gloves.

As we can see from the above discussion, a more informed decision can be made regarding the preferred settings of the controllable factors by coupling the information about the mean response with the variation in the response across levels of a factor. The variance analysis has shown that all the quality characteristics have at least one common adjustment factor between them. It seems that factor B (latex temperature) affects pinholes, mean weight and mean finger thickness. In this particular case, to determine the optimal settings for the glove with multiple characteristics, we cannot adjust the mean level for each characteristic independently without causing other characteristics to deviate further from their target values.

Furthermore, for a glove product, when any one is found defective, it will be discarded regardless of which quality characteristic was out of specification.

Hence, we need to consider other responses simultaneously before deciding the best choice of optimal setting for the process improvement whereby both objectives of maximising the mean and reducing the process variation are the primary goals of this study. Due to conflicts in the factor levels, we have to make a trade-off among pinholes, tensile strength, weight and finger thickness. This conflict will be dealt with in chapter 8.

CHAPTER 6

IMPLEMENTATION

6.1 Introduction

In chapter 5 we discussed the results of the designed experiments in depth and drew several interesting observations regarding the rubber glove production process. The technical knowledge acquired has greatly enhanced our ability to understand and control the process. In this chapter, we intend to concentrate on the practical aspects of implementation procedures that will improve the process and highlight experience learnt from this case study.

So far, we have only focused on the tools and techniques that can be used to affect process improvement. However, quality improvement encompasses a wider issue than just making the product properly. In particular, the people involved in the production processes need to be considered along with the improvement efforts. Apart from raw materials, machinery, building and technology, employees are the most valuable asset for a company, because they have potential. They can determine the success or failure of a company. Without them no work can be done and nothing could be achieved, this is particularly obvious when they go on strike. Consequently, a company can become paralysed. Humans have feelings. Therefore, feelings of satisfaction and importance are an essential part of the improvement objective. So in implementing an improvement programme effectively, a company cannot afford to ignore this element.

6.2 Why Improve?

There are several reasons why improvements are sought by an organisation. One of the key reasons is the desire to meet new customer demands and this is particularly the case with the company where the rubber examination gloves are made. The management has expanded its production areas, invested in new equipment and maximised the use of the equipment. However the amount of scrap was increasing. They reasoned that the technology was getting more complex and that decreased first-time yield was expected. The company selected its best employees to look after the new equipment because it is always much more difficult to rework finished products than it is to do it right first time. Short-term solution was preferable to long-term prevention.

Perhaps some organisations are only interested in giving their customers a good impression that they are doing something positive about quality improvement. For example, SPC charts or quality manuals are presented to their customers to suggest that they are doing something concrete about quality improvement. However, they may not be using these techniques to improve quality more economically. This is a very sad situation, and is an example of where management has misused the tools. This scenario reflects poor understanding and awareness within the company of the purpose of the tools and techniques.

Other reasons for seeking improvement are when the process is frequently out of control or customers are dissatisfied. Only then is quality considered. This type of company only has a short term focus and is a typical example of a "fire fighting" culture which needs to be modified. Management has to take its obligations for quality improvement seriously if it is to be effective over the longer term.

What is usually missing is that the main reason to improve quality is not well establised. Issues like its priorities and how it could be achieved are not addressed.

6.3 Lesson Learnt from Practical Experience on Shop Floor

This study was conducted in a glove manufacturing plant in Malaysia to study the present production process line and to investigate the main control factor levels that affect product quality. Not much time was given to promote participation and full time involvement of the senior management in the project. This is because the company had already implemented a quality system. With this assumption the author did not define sufficiently the ownership of the project and the different responsibilities, functions and roles between the company and the author. Only when the project was launched was it found that the project was not treated as the company's project. Instead it was seen as the author's project. The management did not make it part of the company's business activity, even though the management was supportive and happy to have the author in the plant. The reaction from some of the staff was that they are doing some extra work combining their normal work load with the demands imposed by the project. These are some of the difficulties faced by the author. The lack of awareness and insufficient understanding of the significance and role of quality improvement by top and senior management were major difficulties.

The author took her own initiative to stimulate and form a team which comprised personnel from several departments, such as production, technical and quality assurance. Some of the middle management and operators were co-operative and were keen to be involved. The objective of the project and how it could benefit them was explained. At the supervisory level, they were interested in learning more about the design of experiments so that they could apply it in their work. Later, several brainstorming sessions were held. The author was supposed to act as a "facilitator". That is, to provide problem-solving tools to the manufacturing process. However most of the supervision of the project was the responsibility of the author. This included identification of samples and sometimes collection of samples, even though co-ordination was partly done by the Technical Executive, mainly during the day shift. However, the involvement of senior managers was very minimal. They appeared to be very busy with other meetings and to expect quick solutions. It seems that there was no common sense of mission and direction within the organisation with regard to quality improvement efforts. The Engineering Executive did not see his involvement in quality improvement efforts as relevant. He considers that this is the responsibility of the Quality Executive. Similarly the Production Executive felt that his job is to produce as many gloves as possible and expect the quality assurance department to screen out items not meeting specifications. Both did not recognise that it is much more effective to avoid waste by not producing unusable output in the first place. As mentioned before, this company has installed a quality system which has been accredited, but knowledge on quality management is still lacking. Probably the discipline of quality management is relatively new in Malaysia, and in the rubber gloves industry.

A person working alone would not have achieved much or sustained the interest of the workers in the improvement project. Furthermore, when operating alone, the priorities of each activity may conflict. On the other hand, by working together activities can be focused to better achieve common goals. We discovered that there is much better co-operation when the people who are responsible for implementing the changes are included at the beginning of the planning stages and kept informed throughout the experiment. We also learned that the appointment of a team leader from among the project team members is necessary. One of the supervisors was appointed as a team leader. A team leader would then co-ordinate the work between departments. As an "outsider," executing the experiments, collecting industrial data and getting the samples measured were not easy tasks. It required co-operation among departments. Therefore, direction and authority had to come from the top. That is, an overall quality intention and direction of an organisation have to be formalised by the top management in the form of management quality policy. This is because industrial experiments involve people from cross functional departments, that is, participation from everyone. The author felt that the co-operation given to her while in the plant was satisfactory.

Next, we also realised that all work instructions and forms used during the experiments should be well documented. Documenting instructions was not a problem since the supervisors were familiar with this task. This is one of the strong points that this organisation has to offer. Hence consistent data recording procedures were established. This prevented any confusion or loss of important data. It can also serve as a means of communication.

Another difficulty encountered was that the allocation of time for conducting the experiment on the production line was limited. The author had no idea how long it would take to conduct all the experiments. The author was given two weeks to run the total experiments. Hence, the second replication of the experiments was performed in a hurry. Consequently the addition of water to the coagulation tank was very vigorous, resulting in bubble formation in the tank. Similarly increasing the stirrer speed to ensure uniformity of chemical mixing also led to bubble formation. The time allowed for the bubbles to settle before the actual trials was very short. This partly contributed to why more pinholes were found in the second replicate. Executing experiments on production line was laborious. This was because the preparation of the coagulant solution was done manually. The pumping of the coagulant solution and addition of water were labour intensive. Though changing the latex temperature was not labour intensive, raising its temperature was time consuming. We realised that it was necessary to know the concentration of chemical present in the coagulant tank, before any additional chemicals could be topped up. If the concentration required was out of the specification, we needed to adjust the concentration before running the experiments. The conventional drying method used to dry the samples took about 45 minutes, before results could be analysed.

Some of these difficulties were directly due to the nature of the manufacturing process itself. These practical difficulties could be altered. For example, the concentration of coagulant solution could be controlled automatically by installation of an automatic system for measuring and topping up the chemicals whenever a depletion occured. This automation could reduce time for adjusting the concentration of the coagulation solution. Further, it makes the process operator's job easier, and they could concentrate on their work better. The investment might be high, but in the long term it will pay off. Aside from the practical difficulties, our experience revealed that the conventional drying oven was unsuitable for monitoring the coagulant concentration. A rapid method of drying is necessary, such as an infra-red oven, which takes less then 10 minutes to complete the test.

The most essential and time consuming stage of completing an industrial experiment lies in choosing the main factors and definition of quantitative levels for those factors. This proved to be the case in our implementation.

Though it was difficult to anticipate the actual time required to perform the trial run, estimation for the time required to perform the experiment is essential during the planning stage. Some rough calculation of the time required for the trial could be estimated from the production cycle time. The allowance for some errors in the trial runs should also be taken into account. Tentative arrangement to actually run the experiments should be notified earlier to the production department so as to avoid the production peak time.

Nevertheless, the time required to run the whole experiments on the production line could be improved, if the experimental set-up were approach in a slightly different manner. That is by blocking factors that are labour intensive to change or factors that are time consuming to change. For example, to bring the latex temperature up to requirement takes more than an hour. By blocking we could run all experiments that required this setting before changing the setting. In this way, the frequency of changing the latex temperature is reduced, and hence leads to time saving.

All the experimental trials were carried out and all samples were finally tested. Due to time constraints, all data analyses were performed in Newcastle. A follow-up run to confirm the results of the experiment could not be performed. There are several possible reasons to this response. This is probably due to the physical absence of the author and also the existence of a technological gap: designed experiments are unknown to this company, though one factor experiments have been used by the company. Thus, the company might not have been confident enough to perform the confirmation trials on their production line. Also, no one would want to take the blame if anything goes wrong. Other possible explanations could be that either management has lack of vision, lack of perceived benefit due to insufficient understanding of the value of experimental design, or face difficulty in breaking the "fire fighting" cycle.

6.4 The Human Factor

Employees are the most valuable asset of any company, aside from money, raw materials, machinery, buildings and technology This is because without them no work can be done and nothing can be achieved as previously discussed. Therefore, it might be prudent to invest in people in order to foster co-operation, sense of belonging and loyalty to the company, although many companies and industries argue that if the employees leave them, no tangible benefit is obtained. However, not many would leave if they are satisfied with the company. Seddon and Jackson (1991) reported that one of the main reasons for the effectiveness of Japanese total quality improvement programmes is that they have satisfied employees. This is due to the fact that Japanese management has long recognised the potential of people. They gain benefits through the use of team work such as the quality circle group. Taylor (1994) has demonstrated this point in her efforts to introduce quality improvement programmes in a UK-owned company. She had formed various groups to initiate the improvement programmes and the outcome was very encouraging. She stressed that working as a team is more effective than individual effort and can also improve communication and promote understanding amongst personnel. In this way communication between departments could be addressed simultaneously.

Changes in the organisation may be necessary to create a climate favourable to quality improvement. This demands commitment and hard work. Top management must take steps to ensure that quality happens. They need to exercise management skill. It is one of the most challenging jobs that any executive can take on! It is a relatively new way of managing and it probably means they need to have some training themselves. They should become more involved in understanding specific management techniques. Perhaps more important, is an understanding of managing human processes. The areas of personal, team and organisational development and productive human relationships must be improved. This is necessary not only to foster more effective organisations but also more effective external relationships with customers. Building a total quality management system may appear to be a huge task. In the author's experience, it can be done by breaking it down into specific, achievable steps through the participation of everyone in the company

Nevertheless, the greatest difficulties facing the introduction of total quality management are achieving cultural change and changing management behaviour (Seddon and Jackson 1991). Hence, before the implementation of quality improvement initiatives can occur, "cultural" change is necessary to provide the required management shift for the improvement of quality. This change may face a strong resistance from the work force. This is often the most common and natural human behaviour. Inevitably, this reaction will be an obstacle to any quality improvement projects if it is not eliminated or overcome. According to Ronald (1990), resistance to change is the result of insecurity. He identifies the cause of insecurity as being due to a person being unsure about his or her own ability to do what ever the change requires of him or her. Job security is another reason. Relationships between people are the main source. Any change that can upset the social norms of a particular group is likely to cause insecurity among the groups, or at least to an individual.

In order to overcome this resistance, total participation and leadership from the top management is vital. It has to provide the vision and to drive the change through involvement of everyone in the organisation. Bertram (1991) claimed that the lack of top level commitment is the main reason for more than 80% of failures on quality improvement programmes. Thus top management has to provide the necessary leadership and play an important role in making the program successful (Bertram, 1991). Bounds et al. (1994) commented that many unsuccessful quality improvement programmes have been caused by delegation of education, training, and responsibility for improvement to lower levels of the organisation or to consultants, while managers continue to carry on business as usual. He also said that "Faulty systems and faulty practices by management continue to create conditions within which sustainable improvements cannot be made. Perpetuation of faulty practices by management while the work force is expected to change breeds cynicism in that work force". So improvements can only occur if managers follow the expected behavioural changes themselves.

In the author's experience, training and education are also other means of changing the attitude of people at all levels of the organisation and making them aware of the importance of quality for company survival. It is necessary for management to investigate the need for training aimed at improved knowledge and motivation of the personnel regardless of level and function (from top management to shop-floor). According to a survey conducted by Gandogan et al. (1996), the most negative effect in quality management systems was the lack of performance feedback (86%), lack of education and training (69%) and lack of work motivation (69%). As Owen (1995) pointed out, quality is about an attitude of mind. It is about accepting that there are always ways to improve. During training sessions, management objectives and vision could be introduced and explained to employees as to why they need to adopt new methods and how these could benefit them and make their work easier. Consequently, this could boost their morale and sense of loyalty to the company. According to Lascelles and Dale (1993), "team-based and manager-led workshops and training sessions are the most effective mechanism for deploying education and training". He also added that by tackling real problems and needs, training becomes directly relevant to the work situation.

Team empowerment is another aspect which has to be addressed in the implementation of quality improvement, particularly in the design of experiments. To encourage total participation from employees on the shop-floor, management has to trust them. That is, an operator team for example, should be given certain degrees of authority to solve their own production problems and to implement their solution on their own without need to seek permission from their managers. True empowerment is essential. This obviously would increase the employees' pride and sense of importance, and hence would make them happy because they now play a bigger part in contributing to quality improvement.

As discussed, the development and implementation of quality improvements are not as simple as they seem. They encompass a much broader issue than just making changes to equipment and adjusting factors. This point has been emphasised by Gerson (1996) in the application of SPC in process industries. She argued that SPC is not just about control charts: it includes good communication, proper handling of quality data, sampling, measurement of the finished product and maintenance of equipment and machine. Therefore, the real focus of improvement involves the integration of management participation and employees as well as problem-solving tools and techniques.

6.5 Implementation of Quality Improvement in Malaysian Industry

Approaches to quality control activities which have been undertaken by industries in Malaysia differ according to individual sector, company size and technology bases. The main weakness of these undertakings reported by the Japan International Co-operation Agency (1993) was the lack of sufficient understanding of the significance of quality control activities. Quality control activities are largely undertaken only in response to the demands made by clients. Consequently quality control activities are generally carried out as quality inspection. As long as this state of affairs remain unchanged quality control improvement activities will not advance.

When analysing what is required in Malaysia for pursuing quality improvements in the industrial sector, it is not enough to just consider the current state of the industries with regard to quality activities. It is also important to assess trends of the international economical environment which affects the advancement of industrialisation in Malaysia, and to foresee the future position of the Malaysian industry with consideration also given to the changing international economic environment.

In order for Malaysia to cope with these international industrial trends, it is vital to promote industrial development in the fields in which the country has comparative advantages such as the application of advanced automation in order to assure a production system which maintains competitiveness even under the condition of high cost labour. There should also be specialisation of production in the fields which require extremely advanced technology and high quality, while transferring labour intensive work and production to those countries where cheap labour is abundant.

It is considered difficult for Malaysia to continue to maintain comparative advantage relative to the surrounding countries on the basis of the competitiveness of its labour costs alone since a rise in those costs cannot be avoided. Therefore, the key way out is to provide comparatively high quality human resources at competitive cost. That is, to develop human resource to meet the increasing skill requirements in general, particularly training related to quality control improvements and productivity activities.

The following measures need to be considered in order to realise human resource development.

(1) Formulating a human resource development fund which will provide incentive grants to companies undertaking the training of the work force in basic and new emerging skills as well as retraining for higher skills.

(2) Review the present measures undertaken by the government to encourage the private sector to train their employees to meet the increasing skill requirements. In this connection, the scope of eligibility for the double deduction incentives on approved training introduced in 1986, should be expanded to include training related to quality improvements and productivity activities.

(3) Introducing a levy-grant scheme to encourage greater private sector involvement in training.

(4) Maximising the utilisation of organisational structures which are more effective for enhancing activities for the promotion of quality improvement among industry. Also establish quality enhancement centres with special emphasis on assisting small and medium companies.

Apart from these needs, enhancing the promotion and dissemination of quality awareness on the national scale is also necessary in order to implement quality improvement in Malaysian industry.

One big potential problem involved in training for quality improvement activities is difficulty in communication, such as linguistic. There are very few textbooks or reference works on quality tools and techniques written in local languages, and so the local staff in charge must translate for trainees, and this might slow down and obstruct the promotion of quality improvements. Another problem to some extent is the basic education on statistics , since quality tools rely partly on application of statistical methods. These problems are particularly obvious with the small and medium sized companies.

6.6 Benefits of Quality Implementation Efforts

The technical knowledge acquired regarding the production process has greatly enhanced our understanding and ability to control the process. Since this information provides potential solutions to our investigation, we become more aware of what to control and what not to control. Improvement in the understanding of the process motivate teams and people because they understand why problems happen and what is needed to effect change.

Adjustments can be made to controllable factor levels that have a strong influence on the response. This allows a more efficient way of changing the processes because unnecessary adjustments to non-influential factors are not made. Also, each adjustment has more predictable effects. Hence, this could make life a little easier for the process operators. In fact these parameters could reduce cost. For an example, the oven temperature for pre-heating of the formers need not be too tightly controlled since it has no effect on all the quality characteristics such as pinholes, tensile strength, weight and finger thickness. Therefore, setting the oven temperature lower would utilise less energy. A reduction in the time required to heat up the oven would also be gained. Similarly, the pH of latex also has no influence on the quality characteristics. So keeping the pH value above 10 would reduce the amount of chemical solution used. Both of these aspects are examples of potential cost saving in terms of raw material and energy usage.

The use of designed experiments to acquire technical information is far more effective then the traditional one factor experiment.

There are other advantages as well. The experiments tell process engineers what kind of relationship has been established between inputs and outputs and how to represent this relationship through mathematical models. This extra information can be used to make knowledgeable decisions on the cost/benefit trade-offs of various improvement proposals. It also provides a basis of knowledge and direction for future experimentation. The potential benefits acquired suggest that new equipment is unnecessary to affect improvement in the glove production process. Another spin off from this implementation exercise in terms of management is that managing is made easier. As process problems are eliminated, precious time and resources may be saved. Production scheduling and plans can be made and executed without taking time out for "fire fighting".

6.6 Chapter Summary

Nearly everyone agrees on the benefits of improving quality, however most companies do not have the tools to get the job done. Nevertheless the potentials to obtain gains in all these benefits depend on the implementation strategy. Development and implementation encompasses a wider dimension than just making changes to equipment and adjusting factors. The real focus of improvement involves the integration of management participation and employees as well as training and education. Also, true empowerment is essential to make employees feel important and satisfied. The enormous potential benefits which can be reaped from implementation of quality improvement justifies the effort.

APPENDICES

CHAPTER 7

DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

In recent years, quality has been the key issue to the success of many multi-national organisations. Kanji and Asher (1993) reported that many senior managers in these companies seem to link quality with profitability, customers' needs and low cost. They also perceived quality as a "competitive weapon", and assumed it as part and parcel of long-term strategic planning.

In process control, to get at the root cause of the problem, often we will need to experiment with the process, purposely changing certain factors with the hope of observing corresponding changes in the responses of the process. Sometimes the problem is a system problem. The process is in control, that is, the output is within specification limits, but the variation is too large. This signals a fundamental problem that may not be revealed easily without a comprehensive study of process performance across a range of conditions, and it is often governed by a large numbers of factors. Without an organised and systematic approach to statistical design of experiments, costly and time consuming efforts can lead to little or nothing in terms of enhanced knowledge of the process. Despite the widespread use and economical importance, robust process design has not been applied to the rubber glove manufacturing industry.

The overall objective of this thesis is to understand the process in depth and to discover the changes to operating conditions which may lead to improvements in product quality and consistency and, eventually, reduced wastage and thus improved process efficiency. That is, to identify the main controllable factors that affect the quality characteristics of interest. This case study could be used as a model in planning, and carrying out rubber glove manufacturing process optimisation for quality, cost and manufacturability, particularly for the locally-owned Malaysian rubber glove companies.

In this study, robust process design in the presence of noise is employed to investigate the effects of input variables on the outputs (responses) of the glove process as discussed in chapter 4. Sixteen two-level fractional factorial experiments for varying seven controllable factors and one noise factor simultaneously were performed. Each run represents a combination of controllable factors and their levels. For each experiment a measure of the quality characteristic of interest was taken. The strategy applied in our approach was first to determine those product or process settings which reduce performance variation. Next, the means of adjusting the average to target were then determined. The factors that contribute to variability can be divided into controllable factors and noise factors. Controllable factors are those factors whose settings are within our control; we can adjust them relatively cheaply and easily and once set to their optimum, the setting can be maintained in the future. Noise factors are those factors which cause variation but which are impossible or undesirable to control in actual production. They include manufacturing variations, environmental effects and deterioration over time A product and process that consistently achieves its target performance in spite of these factors is described as being robust against noise.

The study explores and evaluates the interactions between noise and controllable factors that in turn influence the response (output). Their levels that minimised the noise factor effects are further examined and identified. The collection of experimental data is the fundamental activity toward the building and verification of mathematical models. The details of the analysis procedures associated with these designs are extensively discussed in chapter 5. A confirmation run should be conducted to check whether the predicted values agreed with the observed values. However, due to constraint which is beyond our control, we could not perform this run. The author could not be on the plant to perform the confirmation runs. Although the runs could be conducted by the company personnel, it was not done due to reasons discussed in chapter 6.

Apart from technological tools which are just some of the many necessities for ensuring quality, the human factor is another aspect which is a crucial element for the effective implementation of quality improvement programmes. It is therefore essential to organise participation of all employees in quality programme. This requires a management structure which recognises the need for participation and learning throughout the organisation. This should then improve attitude, team building and technical training to produce more involved skilled work force. Nevertheless, top management needs to provide total commitment and leadership to quality improvement efforts, and to ensure that all activities within the system are working towards a common goal. Thus, continuous improvement should be regarded as opportunities and seen as a competitive advantage rather than problems.

7.2 Discussion of Results

In this case study, eight factors were selected for optimisation. These factors and their alternative levels are listed in chapter 4. The effects of the different sets of experimental conditions of the important controllable factors in the presence of noise factors have been analysed. The technique used, ANOVA, has been discussed extensively in chapter 5. The variability of all the response variables of interest, that is tensile strength, finger thickness, pinholes and weight, can be potentially minimised.

An orthogonal array was constructed in the experimental design layout so as to allow a mathematically independent evaluation of the effect of each of the factors. The type of array used in this case and their advantages are discussed in chapter 4. As discussed, we are not interested in the results of one treatment combination, but in the average change in response over a number of experimental trial runs. This enables us to make comparisons of factor levels, at high and low levels for example, under different sets of experimental conditions. It is important to note that to run a full experiment is expensive, time consuming and exhaustive of resources.

If a similar experiment is to be conducted again, the experimental set-up would be approached in a slightly different manner. That is by blocking factors which are labour intensive to change or factors which are time consuming to change. By blocking we could run all the experiments that required this setting before changing the setting. In this way, for example, the frequency of changing the latex temperature will be minimised leading to time saving.

The initial findings from the preliminary data collected prior to conducting the experimental design indicate the presence of additional variability in the process and suggest the presence of batch to batch gloves inconsistencies. The evidence suggests that the additional variations present were not due to chance. Apart from this, we also assessed the process capability and its performance in relation to the specification limits. This result is important because it can provide key areas for potential improvement. Also it forms a basis on which to build or formulate the strategy to reduce variation and to achieve continuous process improvement. As mentioned in chapter 3, we must ensure that we are doing the right thing right first time!

Our preliminary investigation revealed that the process performance index for the tensile strength is greater than one, indicating that the process is capable of producing gloves that meet the tensile specification limit. As regard to the finger thickness, the process performance index is less than one. This explains why variation between each lot occurs. To tackle this problem, the company can either change the process mean or reduced the process variability as discussed in chapter 5. The process average proportion of non conforming product for the pinholes is roughly 1%. The current requirement is AQL of 2.5%. Although it seems that pinholes are below the requirement, constant improvement to reduce the pinholes should be sought. While weight is not a direct customers requirement, it is needed for internal monitoring of 100 pieces gloves per carton. The process capability studies indicate that a weight specification tolerance of $\pm$ 0.2 is quite tight if individual glove weight is to be at 7.7-7.0 gm. If this specification is for the total or average weight of 100 gloves, this is not a problem because the variation within lot is about 0.17 which is less than the specified tolerance. It is necessary to highlight that rubber gloves have multiple quality characteristics which are correlated in some way. Not surprisingly the same process conditions will not be optimum for all the characteristics measured and some compromise may be necessary.

The second phase of the analysis was based on the industrial data with the aim of investigating the effect of the inputs on the outputs in the presence of a noise factor. It was found that the noise factor influences the strength, thickness and pinholes except for the weight of the examination gloves. Inclusion of the noise factor allows us to assess and increase the robustness of the design. The existence of interactions between controllable and noise factor in the mean (location effect) model show that variability induced by noise factor (humidity) could be reduced. This means that we could minimise the response's sensitivity to humidity rather than controlling it. Since the process could function well in the presence of humidity, it is therefore a robust process.

This study also identified two types of factors which contribute to variability. They are factors which affect standard deviations (dispersion effect) and factors which affect the average also called the adjustment factor. The strategy of robust design, for achieving high quality at low cost is first to determine those product or process settings which minimise performance variation. Once this is achieved, we then adjust the factors that influence the mean to the target as necessary. By doing this we could potentially reduce inconsistency. This is where the main problem is and usually alot of money is spent to address this problem.

Our analysis has shown that the tensile strength after ageing is a function of curing oven temperature (A), oven temperature after coagulant dip (G), latex temperature-oven temperature after coagulant dip (BG) and latex temperature-percent calcium nitrate (BD) statistically significant. Factors affecting standard deviation are curing oven temperature profile (A) and humidity (E).

Since factor A affects both variability as well as the mean, it could not be used to adjust the mean to the target. It has to be set at a level giving minimal variation, in this case at the low level. However, the oven temperature after coagulant dip (G) could be used to maximise the mean average because changing the level does not affect the variation. This strategy could result in performance which is on target with minimal variation. With regard to interactions between control and noise factors using mean analysis there is no interaction observed. This suggests that the opportunity to minimise strength sensitivity to humidity through the mean does not exit. Since latex temperature and oven temperature after coagulant dip (BG) interaction is statistically significant, the oven temperature after coagulant dip (G) should be set at its low level. It can be concluded that A, E, F, G and BG were the most significant parameters. The other parameters, former's temperature (C), percent calcium nitrate (D), latex pH (H) and latex temperature (B)) have no significant effect on either the mean or the dispersion of tensile strength. Our process capability studies revealed that the process performance of the tensile strength is greater than one which suggests that the company do not have to monitor this parameter tightly.

Another response under study is the weight. The three main factors B, D, F and one interaction DF have significant effects on the mean glove weight. Factors D and H have significant influence on its standard deviation. Since B and F were significant in the mean analysis but were not in the standard deviation, we conclude that factors B and F could be used to control the weight of the glove without having a detrimental effect on the process variability. Also, because both of the estimates of the effects of B and F are positive, increasing either or both of B and F will cause an increase in the weight mean while decreasing either B or F will lower the process mean.

Pinholes on the other hand are affected by factors A, B and G. Lowering factors A and B minimised pinholes while increasing oven temperature after coagulant dip (G) tends to produce fewer pinholes. In this particular case, pinhole counts follow a Poisson distribution. Its standard deviation is equal to the square root of its mean. If the mean decreases, the standard deviation will also decrease. Hence, when there is less pinholes, there will be less variability in the process. There is significant interaction between the noise and the controllable factor B. This suggests that the process can be made robust to changes in humidity (E) by adjusting B. The results showed that the average pinholes could be reduced from 1 percent to 0.01 percent. This improvement represents a potential 99.0 percent reduction in pinholes.

With the finger thickness, factors D and B have significant influence on its mean response. Setting both B and D at high levels would increase the mean finger thickness. The effects of B and D on the finger thickness are linear. None of the factors has significant effect on the standard deviation. Again there is strong interaction between noise and controllable factor B, suggesting that this process is sensitive to noise. It can be concluded that factors B and D are the only important parameters.

We had observed that humidity influences both the mean thickness and pinholes. Setting the latex temperature (B) at an appropriate level could minimise the sensitivity of the process to humidity. A possible explanation for the finger thickness variation at night is that the temperature decreases therefore humidity (relative) increases. This means we have high percent of moisture content in the air. When the latex in the dip tank is exposed to the atmosphere, evaporation from the latex tank takes place but at a slower rate. So the rubber particles in the latex are more stable and packed closer together when the latex temperature is increased. Consequently the amount of calcium nitrate that diffuses through these particles in the latex is less than when the temperature of the latex is increased. The rubber particles are not tightly packed together. Therefore more calcium nitrate can diffuse through the latex and thicker gloves are obtained. The results of this study are also consistent with the results of Gorton and Iyer (1973) and Blackley et al. (1982) which revealed that the thickness of latex film by coagulant dipping depends on ionic diffusion of the coagulant. It is important to note that the main driving force is the two positively charged ions of the coagulant.

Another phenomena that we observed concerned the pinholes. Possible explanation for the percent pinholes to vary due to the effect of humidity during the day is as follows. During the day time temperature increases. Consequently the moisture content in the air decreases. The moisture of the latex in the tank evaporates more rapidly in the day than at night. As a result the latex viscosity will increase. By applying more heat to the latex, evaporation is enhanced and the latex's viscosity increases further. As the viscosity increases, probably the process-ability and wetting property of the latex are affected. Hence the formers will not be wet properly and this leads to pinholes.

This study suggests that finger thickness has linear correlation with the weight and likewise, pinholes and strength. The results show that thickness and weight have a significant correlation, whereas it was not very significant for pinholes and strength. We found that some controllable factors can be manipulated to minimise variability while others can be used to bring the process to maximise the output. From these observation the optimum condition selected after considering all the quality characteristics was $A_1B_1C_1D_1F_2G_2H_2$.

The coagulant solution contains both calcium nitrate and calcium carbonate. The current variation in concentration levels of calcium nitrate in the coagulant solution obtained from the normal production line is shown in Figure 7.1. Figure 7.1 indicates that there was some evidence of variation in coagulant concentration during day to day production. Although the data does not appear to show extreme coagulant concentration levels, the concentration levels seem to be on the higher side of the operating specification which was 7.0-14.0 percent for calcium nitrate.

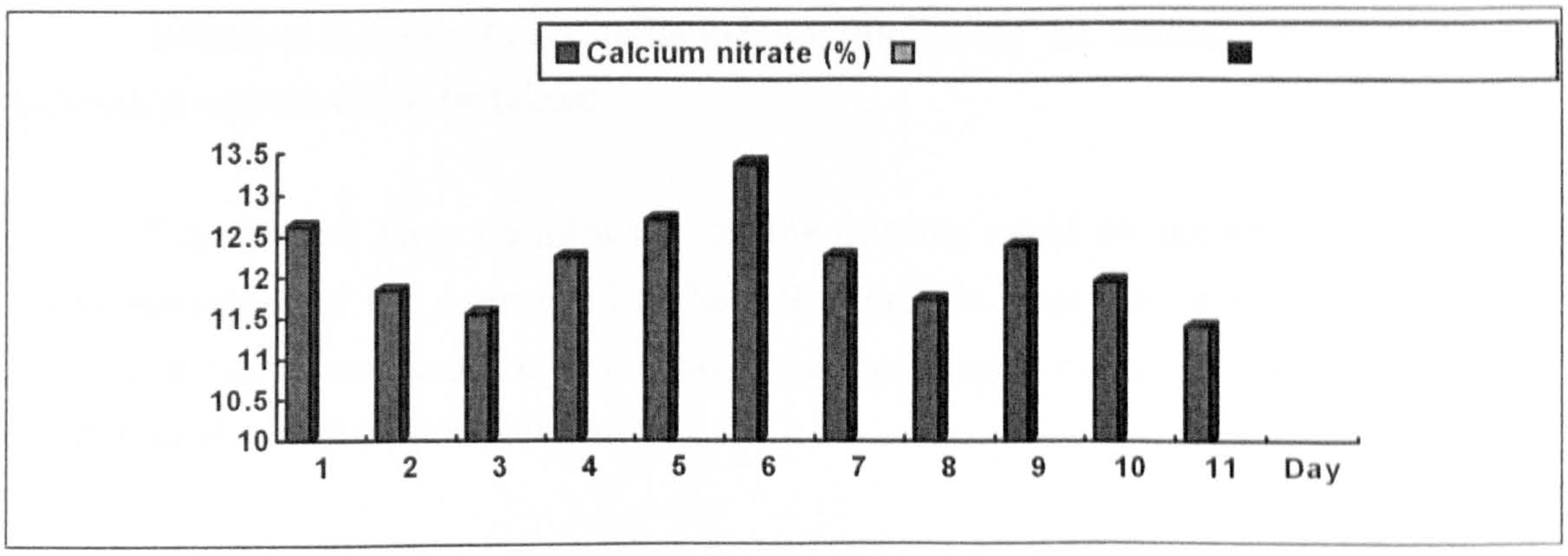


Figure 7.1 Concentration Levels of Calcium Nitrate in the Coagulant Solution

Our experimental range for calcium nitrate was between 7.0 - 8.0 percent for the lower level and 11.0-12.0 percent for high level Operating between the levels and vice-verse could cause significant changes. Figure 7.2 demonstrates how glove thickness varies with the concentration of nitrate.

This finding showed clearly that the present operating range specified by the company could affect production capability. Further, the experimental results indicate that the thickness of the glove conformed to product specification even at a lower calcium nitrate concentration, that is 7.0-8.0 percent. This means that less chemicals would be needed to produce the same quantity of gloves. Another advantage is that lower concentrations of chemicals would reduce the accumulation of particles at the bottom of the tank. This could reduce the clogging of the screen in the coagulant tank. Eventually the production downtime could be minimised in between productions.

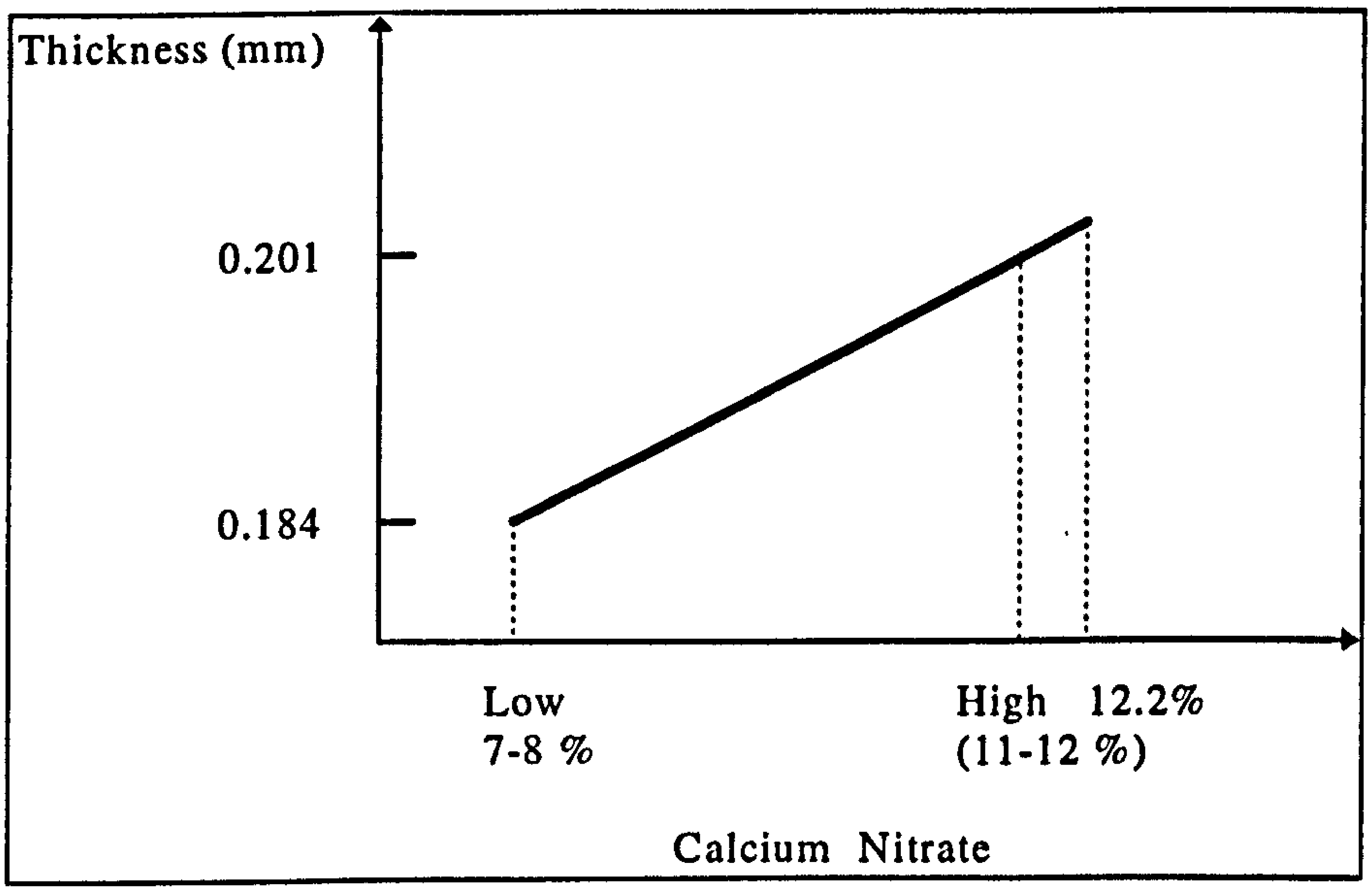


Figure 7.2 Glove Thickness versus Calcium Nitrate Concentration

Based on the potential benefits that are implied by the findings of this work, the following actions could be taken:-

(1) Factors that have no influence on the outputs could be relaxed. For example the temperature of the oven used to heat the formers does not require tight control. Setting the oven temperature lower would reduce energy costs and the time required to heat up the oven will be shorter.

(2) The company current practice for the formulation of the coagulant solution is 12.2 percent of calcium nitrate. The experimental results showed that at 7.0-8.0 percent of calcium nitrate, the glove finger thickness could still be achieved within the specification (0.18 mm). Therefore a saving of 4.2 percent of calcium nitrate could be made, if it is implemented. Every one million pieces of gloves require 400 kg of calcium nitrate. Therefore a production rate of 240 million pieces per year will require 96,000 kg. If one kg of calcium nitrate costs $2.70 Malaysian Ringgit (MR), then a reduction of 4,032 kg will give a saving of $11,279MR per year, without any initial cost and effort.

(3) The installation of an on-line automatic system for measuring and topping up chemicals whenever they are depleted could drastically reduce downtime cause by coagulant concentration adjustment. If at present the downtime is two hours per day and 5000 pieces are produced in an hour then 40 man hours could be saved in a month. Moreover during this period, 200,000 pieces of gloves could be produced per production line. Thus more saving could be made if more lines are automated.

The automation system will require a sensor, stirrer for the topping tank and a displacement unit to top up the coagulant tank. This investment will not be substantial compared to the potentially enormous benefit that could be gained as quantified above. Process operators could be deployed to do more productive work. Alternatively, a reduction in manpower requirements could alleviate the labour shortage problem.

Another alternative to speed up the measurement of coagulant concentration is to replace the conventional drying method with an infra-red oven. Present practice requires 45-60 minutes to get the results, while an infra-red oven only need 10 minutes.

7.3 Conclusions

This study has attempted to improve the current performance of a rubber glove manufacturing process in general and in particular, for small and medium scale systems. The approach of this study was based upon and developed around the philosophy of prevention and building in quality in the product and process rather than engineering out problems later. Sources of variation in the process were investigated. Details of robust designed experiments and selection of factor level settings were described. Guidelines for the implementation of the improvement efforts were discussed. The results gathered from this study were analysed using the ANOVA. The models which described the relationships between the inputs and the output variables were developed. Experience learnt during the implementation stage and the role of the human factor in the effective implementation of quality improvement efforts were highlighted.

The main conclusions resulting from this study are as follows:-

(1) The inclusion of noise factor in this study has provided crucial information and enhanced our understanding for choosing the appropriate process factors and their levels in rubber glove manufacturing. It shows that humidity could potentially influence the mean response of pinholes and finger thickness. In all cases, the results of the study have shown that the variability in the responses could be minimised and there is significant potential for improvement.

(2) The results from this study suggest that the oven temperature after coagulant dip has the largest influence on both the mean tensile strength and pinholes. Percent calcium nitrate has the largest influence on the mean weight and finger thickness, while the formers' oven temperature does not affect any of the quality characteristics of concern. Hence this parameter does not have to be controlled tightly.

(3) The study has emphasised that the rotation of the stirrer in the coagulant tank could contribute to the creation of air bubbles. Therefore the speed of the stirrer in the coagulant tank has to be kept sufficiently low in order to keep the pinholes level low.

(4) This study suggests that finger thickness is linearly correlated with the weight and likewise, pinholes and strength. The results show that thickness and weight have a significant correlation, whereas it was not very significant for pinholes and strength.

(5) It also revealed that humidity influences pinholes and finger thickness. The discovery of interactions between controllable factors and humidity, suggest that the process can be made robust to changes in humidity by adjusting the latex temperature.

(6) The results suggest that some of the models developed from this study could potentially be used to facilitate changing manufacturing parameters to cope with changing customers' specifications.

(7) The practical experience gained in this study suggests that everyone in the organisation is responsible for quality. That is, not only managers who are responsible for quality but also the employees who can actually make quality happen. It is therefore important to educate employees at all levels. For an example, if the cleaner does not perform his or her work properly particularly in the "clean room" where sorting is done, dust accumulation and cleanliness of the tables could affect microbial count. The first objective of educating them is to influence their attitudes, values and outlooks. The rationale for this approach is that if employees are to be committed to any effort for improvements, they must understand the reasons why

improvement is necessary. They must understand how they will benefit from the redesign of organisational systems, processes and method of doing work. Their work have to be presented in concepts that enable them to see the effect of their work differently and allow them to better interpret the information they use to carry out their work. Once the need for improvement is felt by every employee they would support, participate fully and be committed to the quality improvements programmes.

The next essential elements is to provide training and guidance in the use of tools and methods for improvements such as problem solving, information and knowledge about the products, materials, manufacturing processes etc. It is necessary for management to investigate the need for training aimed at improved knowledge and motivation of the personnel regardless of level and function.

(7) This study also demonstrates that responsibility for quality starts at the top and for it to be successful, it needs firm and clear leadership. There has to be a consistent approach to quality which is clearly defined and understood by all. This can only come from top management. To make it happen, they need to define their policy, be committed to it and be involved in making it happen. As identified by Oakland (1993) and Bertram (1991), if top management fails to recognise the importance of quality improvements, it will be difficult to implement the program.

(9) Another essential element in implementing this program is communication. That is, both formal and informal lines of communication between senior and junior employees. For example any changes or modification in the concentration of a chemical, change of material, formers knocking each other along the driven chains etc. Should be fed back to line operators as quickly as possible so that the same mistake will not happen again.

This study suggests that there is substantial room for improvement in rubber glove manufacturing. The additional knowledge gained would therefore provide greater insight into the present operation of the manufacturing process. This thesis has identified the controllable factors and their levels affecting pinholes, tensile strength after ageing, finger thickness and weight of the gloves. It has also revealed that pinholes and finger thickness can be potentially made robust to humidity by adjusting latex temperature. However confirmation runs of the results obtained from the experiments were not performed due to time and financial constraints. Nevertheless, the models developed from this study have high potential to predict future data well. Finally the project has reinforced the fact that the human factor plays a major role for effective implementation of quality improvements in an industrial environment. These findings will be presented to the rubber glove manufacturing company to instigate the improvements suggested in this work (see Appendix 5)

7.4 Recommendations for Future Work

Based on the conclusions from this study, the following are proposed for future work:-

(1) An obvious area of future work is to implement the results gathered in this study in the company. The performance of the process can then be monitored using control charts that can handle two or more responses (quality characteristics) simultaneously. They would reveal whether the process is out of control and factors could be adjusted to bring the process mean back into control without affecting the process variability.

(2) The variances and the means of different responses were modelled using regression analysis. However, the results from the experimental case studies revealed that the variance models were statistically weaker. The results impose restrictions on the use of the variance models for the prediction of the dispersion setting. Further investigation of this limitation in future process application is required.

(3) Due to constraints the following were not investigated but should be considered in future work:-

(a) A survey should be conducted by means of a questionnaire or personal interview on the quality management aspects. This would enhance our findings on the employees attitudes towards their job, their expectations and top management's commitment to quality improvements programs before and after implementation.

(b) In this study, the improvements that could be achieved were not formally evaluated. This could be measured by either looking at the real savings through waste reduction, decreased internal operating costs or minimisation of response times to customer needs.

(c) Apply star design to further explore optimisation at 3-levels.

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APPENDICES

Appendix 1

L16 Interaction Table

Column number	Column number													
	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	3	2	5	4	7	6	9	8	11	10	13	12	15	14
2		1	6	7	4	5	10	11	8	9	14	15	12	13
3			7	6	5	4	11	10	9	8	15	14	13	12
4				1	2	3	12	13	14	15	8	9	10	11
5					3	2	13	12	15	14	9	8	11	10
6						1	14	15	12	13	10	11	8	9
7							15	14	13	12	11	10	9	8
8								1	2	3	4	5	6	7
9									3	2	5	4	7	6
10										1	6	7	4	5
11											7	6	5	4
12												1	2	3
13													3	2
14														1

Note: If factors are placed in column 1 and 3 then the interaction table shows that their interaction is in column 2. Similarly column 6 and 7 have an interaction in column1 (source Grove and Davis 1992)

Appendix 2

Plan Based on L16(2^{15}) Layout

			Columns												
No.of factors	Resolution number		C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
6	1V	B	AXB	C	AXC	AXE	E	D	AXD	AXF	F	CXD			CXF
			CXE		BXE	BXC			BXF	BXD		EXF			DXE
			DXF												
7	1V				DXG	FXG			CXG	EXG		AXG	G		BXG
8	1V		GXH		FXH	DXH			EXH	CXH		BXH		H	AXH

Note: The table shows main factors and two-factor interactions only. For example B, C, D and etc = main factor, AXB = two factors interaction between factors A and B. For 8 factors using resolution IV all the main factors for an example B,C, D etc are not aliased to each other. The 2-factor interactions such as AXB, CXE, DXF and GXH in column 3 are aliased to each other. These interaction are physically unlikely to occur except for DXF (percent calcium nitrate-percent calcium carbonate interaction).

Appendix 3

Preliminary Data

TENSILE STRENGTH

Group	Measurements			Mean	Standard deviation
1	28.90	28.90	27.80	28.533	0.635
2	25.90	27.40	27.70	27.000	0.964
3	26.60	24.70	25.60	25.633	0.950
4	28.70	27.70	27.30	27.900	0.721
5	25.90	27.90	26.50	26.767	1.026
6	28.00	26.30	24.30	26.200	1.852
7	27.60	24.30	26.50	26.133	1.680
8	24.50	31.20	30.00	28.567	3.573
9	23.30	23.40	25.60	24.100	1.300
10	24.50	25.00	23.30	24.267	0.874
11	28.00	27.50	28.10	27.867	0.322
12	26.30	28.10	27.50	27.300	0.917
13	25.70	23.20	25.10	24.667	1.305
14	25.10	25.10	26.50	25.567	0.808
15	26.90	27.80	29.90	28.200	1.540
16	24.90	26.90	26.90	26.233	1.155
17	29.30	25.70	29.30	28.100	2.079
18	30.90	29.40	31.10	30.467	0.929
19	27.70	25.50	29.20	27.467	1.861
20	26.60	23.50	27.00	25.700	1.916
21	27.10	26.50	28.40	27.333	0.971
22	27.50	27.40	26.80	27.233	0.379
23	28.00	27.60	28.60	28.067	0.503
24	29.30	29.90	28.90	29.367	0.503
25	31.50	29.20	28.10	29.600	1.735

$$\bar{\bar{x}} = 27.131$$

$$S_B = 1.6273$$

$$S_w = \sqrt{[1/25(0.6351^2 + 0.9644^2 + 0.9504^2 \ldots\ldots + 1.7349^2)}$$
$$= 1.4029$$

FINGER THICKNESS

Group	Measurements (mm)				Mean	Standard deviation
1	0.2165	0.2140	0.2135	0.2200	0.2162	0.0032
2	0.2230	0.2400	0.2110	0.2225	0.2241	0.0119
3	0.2260	0.2280	0.2330	0.2230	0.2275	0.0042
4	0.2320	0.2110	0.1985	0.2005	0.2105	0.0154
5	0.1935	0.2290	0.2425	0.2025	0.2169	0.0228
6	0.2332	0.2025	0.1985	0.2125	0.2117	0.0155
7	0.2235	0.2030	0.2185	0.2190	0.2160	0.0090
8	0.2030	0.2275	0.2060	0.2055	0.2105	0.0114
9	0.1885	0.2015	0.2040	0.2055	0.1999	0.0078
10	0.2195	0.1670	0.2045	0.1925	0.1959	0.0221
11	0.2005	0.2425	0.1935	0.2085	0.2113	0.0217
12	0.2210	0.1965	0.2295	0.2040	0.2128	0.0152
13	0.2065	0.1960	0.2095	0.2050	0.2043	0.0058
14	0.2180	0.1990	0.1960	0.1925	0.2014	0.0114
15	0.2020	0.2060	0.1890	0.1955	0.1981	0.0075
16	0.2020	0.2350	0.2095	0.2230	0.2174	0.0146
17	0.1960	0.1930	0.2015	0.1910	0.1954	0.0046
18	0.1875	0.2010	0.1955	0.2040	0.1970	0.0073
19	0.2370	0.2255	0.1990	0.1845	0.2115	0.0240
20	0.1590	0.1955	0.1995	0.1980	0.1880	0.0194
21	0.1975	0.1965	0.2255	0.2095	0.2073	0.0135
22	0.1795	0.2140	0.1975	0.2030	0.1985	0.0144
23	0.2065	0.2065	0.1920	0.2370	0.2105	0.0189
24	0.2120	0.1935	0.1985	0.2115	0.2039	0.0093
25	0.1955	0.1945	0.2060	0.2125	0.2021	0.0087
26	0.2222	0.1890	0.1925	0.1930	0.1992	0.0154
27	0.1975	0.1920	0.2020	0.1985	0.1975	0.0041
28	0.1950	0.2045	0.1925	0.1950	0.1968	0.0053
29	0.2030	0.1886	0.2030	0.2230	0.2044	0.0142
30	0.2050	0.2260	0.2195	0.1960	0.2116	0.0136
31	0.1995	0.1910	0.1980	0.1895	0.1945	0.0050
32	0.1960	0.2205	0.2010	0.2190	0.2091	0.0125
33	0.1950	0.2050	0.1930	0.1850	0.1945	0.0082
34	0.1930	0.1955	0.2025	0.1960	0.1968	0.0041
35	0.1955	0.2020	0.2025	0.2105	0.2026	0.0061
36	0.2065	0.2250	0.2025	0.1845	0.2046	0.0166
37	0.2015	0.1925	0.1880	0.1950	0.1943	0.0056
38	0.1865	0.2520	0.2225	0.2275	0.2221	0.0270
39	0.2120	0.2020	0.1925	0.2215	0.2070	0.0125
40	0.2030	0.2055	0.1935	0.1975	0.1999	0.0054
41	0.2005	0.2160	0.1995	0.1900	0.2015	0.0108
42	0.2570	0.1910	0.2245	0.2040	0.2191	0.0288
43	0.2155	0.1885	0.2025	0.2095	0.2040	0.0116

44	0.2125	0.2110	0.1930	0.2030	0.2049	0.0090
45	0.2030	0.1925	0.2060	0.1845	0.1965	0.0099
46	0.1980	0.2110	0.2130	0.1950	0.2043	0.0091
47	0.1960	0.2020	0.2150	0.2270	0.2100	0.0138
48	0.2475	0.2280	0.2100	0.2070	0.2231	0.0187
49	0.1965	0.1925	0.2265	0.2005	0.2040	0.0154
50	0.1820	0.1985	0.2350	0.1920	0.2019	0.0231
51	0.1900	0.1870	0.2015	0.1880	0.1916	0.0067
52	0.2090	0.2270	0.1910	0.2105	0.2094	0.0148
53	0.2050	0.2060	0.2015	0.2345	0.2116	0.0153
54	0.2130	0.2305	0.2065	0.2015	0.2129	0.0127
55	0.2240	0.2215	0.2080	0.2255	0.2198	0.0080
56	0.1980	0.2000	0.2000	0.1970	0.1988	0.0015
57	0.1950	0.2195	0.2455	0.2215	0.2204	0.0206
58	0.2270	0.2470	0.1965	0.1925	0.2158	0.0259
59	0.1920	0.1985	0.2250	0.2250	0.2101	0.0174
60	0.2360	0.2350	0.2220	0.1955	0.2221	0.0189
61	0.1945	0.1920	0.1865	0.1850	0.1895	0.0045
62	0.2185	0.2115	0.2185	0.2150	0.2159	0.0034
63	0.1990	0.2080	0.1890	0.1975	0.1984	0.0078
64	0.2400	0.2105	0.2015	0.1975	0.2124	0.0192
65	0.1935	0.1975	0.1935	0.2210	0.2014	0.0132
66	0.2245	0.2245	0.2440	0.1960	0.2223	0.0198
67	0.2085	0.1935	0.1995	0.1985	0.2000	0.0062
68	0.1915	0.2425	0.1970	0.1805	0.2029	0.0273
69	0.2145	0.2340	0.2100	0.1910	0.2124	0.0176
70	0.2080	0.2140	0.2060	0.2400	0.2170	0.0157
71	0.2275	0.2490	0.2110	0.1925	0.2200	0.0240
72	0.1895	0.2015	0.1970	0.2010	0.1973	0.0055
73	0.1970	0.1920	0.1860	0.2180	0.1983	0.0139
74	0.1955	0.1980	0.1895	0.2025	0.1964	0.0054
75	0.1970	0.2030	0.2020	0.2350	0.2093	0.0173
76	0.1985	0.2230	0.2040	0.1940	0.2049	0.0128
77	0.2140	0.2055	0.2385	0.1950	0.2133	0.0185
78	0.2375	0.2075	0.1945	0.2090	0.2121	0.0181
79	0.2125	0.2025	0.2040	0.2005	0.2049	0.0053
80	0.2070	0.2450	0.2055	0.1950	0.2131	0.0219

$$\bar{\bar{x}} = 0.2068$$

$$S_B = 0.0091$$

$$S_w = \sqrt{[1/80(0.0032^2 + 0.0120^2 + 0.0042^2 \ldots\ldots\ldots\ldots + 0.0219^2)]}$$

$$= 0.0146$$

WEIGHT

Group	Measurements				Mean	Std Dev
1	8.37	8.19	8.37	8.38	8.328	0.092
2	8.29	8.17	8.41	8.08	8.238	0.144
3	8.25	8.08	8.28	8.24	8.213	0.090
4	8.38	8.30	8.36	8.10	8.285	0.128
5	7.98	8.20	8.20	8.03	8.103	0.114
6	8.35	8.38	8.50	8.10	8.333	0.168
7	7.95	8.26	8.10	8.21	8.130	0.137
8	8.04	8.20	7.98	7.78	8.000	0.174
9	7.82	8.13	8.26	7.86	8.018	0.212
10	8.05	8.23	8.12	8.06	8.115	0.088
11	7.75	7.91	8.07	8.02	7.937	0.142
12	8.15	7.86	8.07	7.99	8.018	0.124
13	8.10	7.81	8.13	7.82	7.965	0.174
14	8.02	8.09	7.96	8.09	8.040	0.063
15	7.73	8.04	8.20	7.98	7.988	0.195
16	7.90	7.82	7.90	7.89	7.878	0.039
17	7.80	8.11	8.05	8.07	8.008	0.141
18	7.96	7.99	7.99	7.85	7.948	0.067
19	8.02	7.70	7.92	7.88	7.880	0.134
20	8.00	7.86	8.07	8.02	7.988	0.090
21	8.17	8.06	7.90	7.79	7.980	0.168
22	7.56	7.72	7.69	7.58	7.638	0.079
23	7.75	8.07	7.72	7.80	7.835	0.160
24	8.24	7.72	7.86	7.75	7.893	0.239
25	7.65	7.85	7.93	8.02	7.863	0.158
26	7.89	7.66	7.96	7.93	7.860	0.136
27	8.33	7.84	8.12	8.12	8.103	0.201
28	7.82	7.99	7.86	7.65	7.830	0.140
29	7.90	7.87	7.66	7.87	7.825	0.111
30	7.71	7.80	7.98	7.94	7.858	0.125
31	8.07	7.98	7.61	7.90	7.890	0.199
32	7.96	7.84	8.05	7.80	7.913	0.114
33	7.72	7.98	7.66	7.79	7.788	0.139
34	8.15	7.93	7.95	8.19	8.055	0.134
35	7.99	7.77	8.20	7.81	7.943	0.197
36	8.12	8.16	7.96	7.85	8.023	0.144
37	8.26	8.01	7.88	8.01	8.040	0.159
38	7.83	8.08	8.14	8.08	8.033	0.138
39	8.20	8.02	8.23	7.91	8.090	0.152
40	8.40	8.24	7.83	8.08	8.138	0.243
41	8.01	7.91	7.78	7.91	7.903	0.094
42	7.94	8.00	7.98	8.01	7.983	0.031
43	8.29	7.75	7.96	8.21	8.053	0.246

44	8.28	7.83	7.62	7.68	7.853	0.298
45	8.35	7.84	8.04	7.88	8.028	0.232
46	8.10	7.85	8.09	8.22	8.065	0.155
47	8.21	8.27	8.44	7.68	8.150	0.328
48	8.13	7.76	8.06	7.90	7.963	0.166
49	7.70	8.05	8.00	8.23	7.995	0.220
50	7.67	7.95	7.99	7.94	7.888	0.147
51	7.92	7.54	7.96	7.99	7.853	0.210
52	7.95	7.80	7.75	8.30	7.950	0.248
53	8.03	7.92	7.84	7.89	7.920	0.080
54	8.02	8.04	8.18	7.82	8.015	0.148
55	8.04	8.08	7.78	7.92	7.955	0.135
56	7.84	8.09	7.72	8.28	7.983	0.251
57	7.88	8.07	8.08	8.16	8.048	0.119
58	7.86	8.05	7.90	8.13	7.985	0.127
59	7.95	8.04	7.72	8.00	7.928	0.143
60	8.05	8.12	7.77	8.25	8.048	0.203
61	7.74	8.16	7.60	7.97	7.868	0.248
62	7.96	8.03	7.95	8.25	8.048	0.140
63	8.07	8.32	8.07	8.32	8.195	0.144
64	7.92	8.37	7.82	7.72	7.958	0.287
65	8.19	8.20	7.76	7.95	8.025	0.211
66	8.24	7.96	8.14	7.89	8.058	0.161
67	7.95	7.78	8.40	7.91	8.010	0.270
68	7.95	7.90	7.86	8.04	7.938	0.078
69	7.63	8.26	8.00	7.99	7.970	0.259
70	7.84	8.15	7.98	7.62	7.898	0.224
71	7.75	7.98	8.02	7.83	7.895	0.127
72	7.93	7.84	7.59	8.23	7.898	0.264
73	7.79	8.23	7.68	7.61	7.828	0.278
74	7.81	7.73	8.10	8.03	7.918	0.176
75	8.11	7.92	7.99	8.07	8.023	0.085
76	8.13	7.66	8.02	7.79	7.900	0.214
77	8.06	7.99	7.86	8.24	8.038	0.158
78	8	7.9	7.84	8.01	7.938	0.082
79	8.22	7.87	8.33	8.45	8.218	0.250
80	8.05	8.01	7.86	7.94	7.965	0.084

$$\bar{\bar{x}}_{i.} = 7.9893$$

$$S_B = 0.1229$$

$$S_w = \sqrt{[1/80(0.0918^2 + 0.1436^2 + 0.0899^2 \ldots\ldots 0.0835^2)}$$
$$= 0.1742$$

PINHOLES

Group	No.of Pinholes	Group	No.of Pinholes
1	0	31	0
2	0	32	0
3	0	33	0
4	0	34	0
5	2	35	0
6	2	36	0
7	1	37	0
8	1	38	0
9	0	39	1
10	2	40	0
11	1	41	0
12	2	42	0
13	1	43	0
14	1	44	1
15	0	45	0
16	0	46	1
17	0	47	0
18	0	48	0
19	0	49	1
20	0	50	0
21	0	51	0
22	0	52	0
23	1	53	0
24	0	54	0
25	0	55	0
26	0	56	0
27	0	57	0
28	0	58	0
29	0	59	0
30	0	60	0

Appendix 4

Half-normal Plots Data

(A) SQUARE ROOT PINHOLES (%)

Factors	Effects	Half -normal Contrasts	
	15	15	14
C	0.0032	0.041	0.044
BG	0.0045	0.124	0.133
H	0.0120	0.208	0.223
E	0.0157	0.293	0.314
F	0.0160	0.380	0.409
BD	0.0237	0.471	0.507
D	0.02461	0.566	0.611
CD	0.0359	0.666	0.722
AE	0.0445	0.773	0.843
AB	0.0454	0.891	0.977
BF	0.0509	1.022	1.133
A	0.0547	1.175	1.323
BE	0.0703	1.361	1.577
B	0.0705	1.612	2.015
G	0.0976	2.043	

(B) TENSILE STRENGTH (MPa)

Factors	Effects	Half-normal Contrasts	
	15	15	14
CD	0.0178	0.041	0.044
C	0.0408	0.124	0.133
B	0.0780	0.208	0.223
BE	0.0948	0.293	0.314
BF	0.1635	0.380	0.409
AE	0.1781	0.471	0.507
D	0.2656	0.566	0.611
F	0.2928	0.666	0.722
DF	0.3428	0.773	0.843
E	0.3927	0.891	0.977
H	0.4884	1.022	1.133
BD	0.7114	1.175	1.323
A	0.9218	1.361	1.577
BG	1.2406	1.612	2.015
G	1.6847	2.043	

(C) THICKNESS (mm)

Factors	Effects	Half-normal Contrasts	
	15	15	14
BD	0.000484	0.041	0.044
F	0.001122	0.124	0.133
BG	0.001322	0.208	0.223
H	0.001334	0.293	0.314
AB	0.001516	0.380	0.409
AE	0.001522	0.471	0.507
G	0.001597	0.566	0.611
CD	0.001890	0.666	0.722
A	0.002047	0.773	0.843
C	0.002328	0.891	0.977
E	0.002816	1.022	1.133
BF	0.003916	1.175	1.323
BE	0.004490	1.361	1.577
B	0.006772	1.612	2.015
D	0.01685	2.043	

(D) WEIGHT (gm)

Factors	Effects	Half-normal Contrasts	
	15	15	14
BE	0.0031	0.041	0.044
G	0.0071	0.124	0.133
CD	0.0082	0.208	0.223
BF	0.0123	0.293	0.314
AE	0.0238	0.380	0.409
C	0.0269	0.471	0.507
BG	0.0331	0.566	0.611
E	0.0379	0.666	0.722
A	0.0456	0.773	0.843
H	0.0596	0.891	0.977
BD	0.0628	1.022	1.133
F	0.1148	1.175	1.323
DF	0.1174	1.361	1.577
B	0.1733	1.612	2.015
D	0.6291	2.043	

Appendix 5

Outline of Presentation to Rubber Glove Manufacturing Company

THE POTENTIAL FOR IMPROVING THE RUBBER GLOVE MANUFACTURING PROCESS

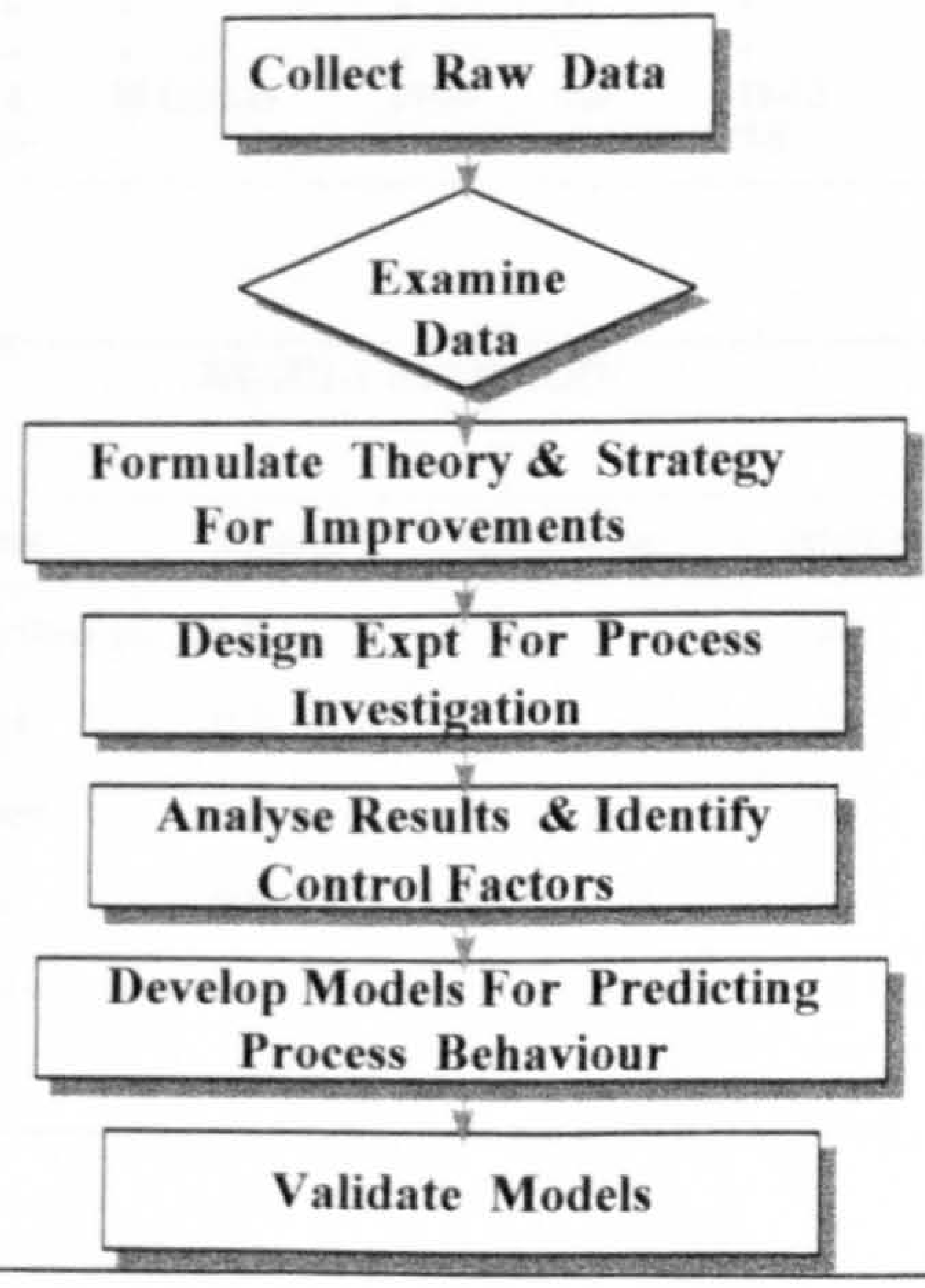
BY

ZAHARAH WAHID

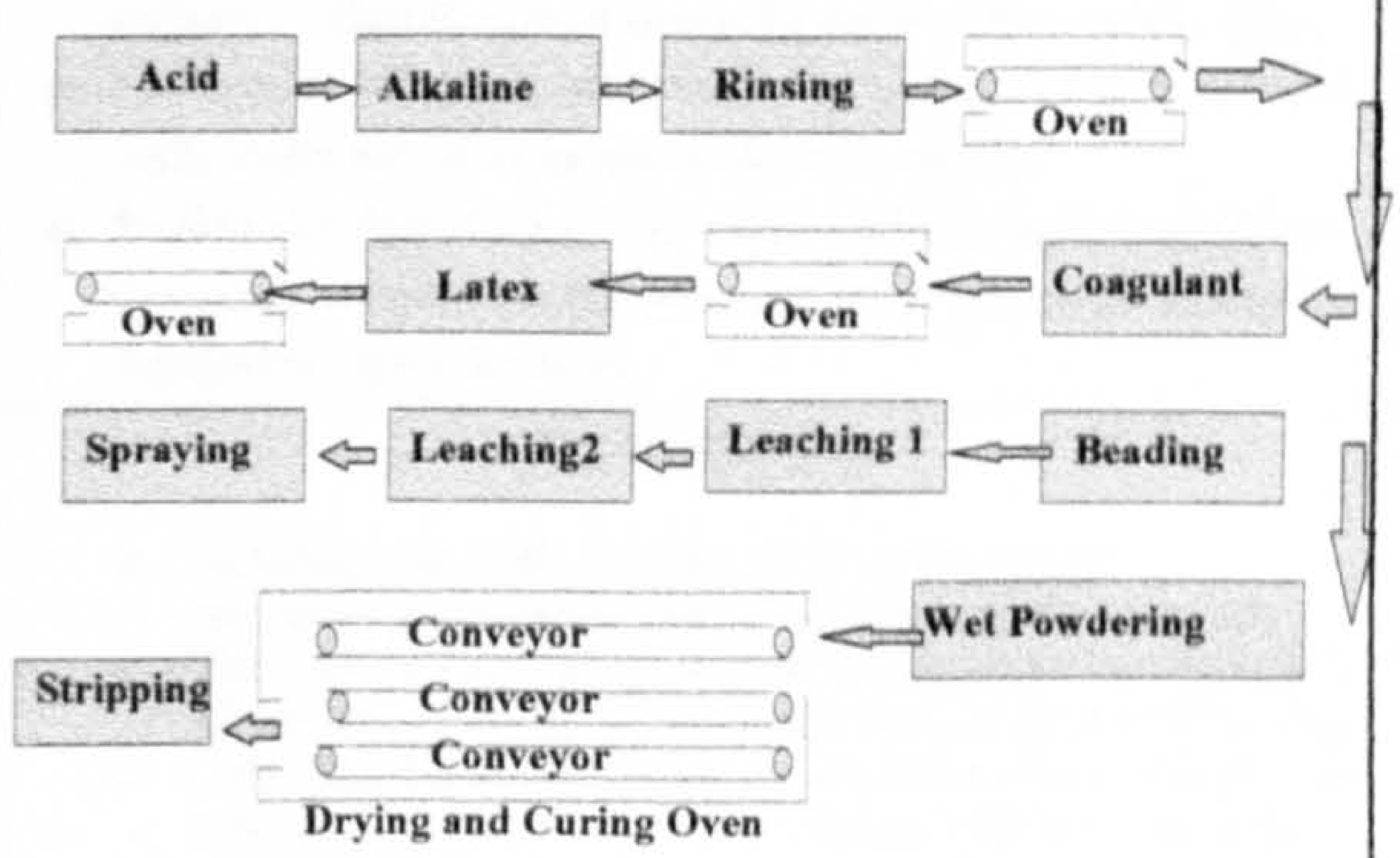
INTRODUCTION

- **To be globally competitive an effective and efficient stratagies are needed.**
- **Quality is the key issue in the success and growth of many multi-national organisation.**
- **Better way to improve quality is to design and build it into the product.**
- **Could achieve a better quality at low cost.**

APPROACH TO THE PROBLEM



RUBBER GLOVE MANUFACTURING PROCESS



FACTORS & LEVELS FOR RUBBER GLOVE EXPT

FACTORS	LEVELS	
	LOW (-)	HIGH (+)
Curing Temp Profile (A)	80 100 115 115 120 130 °C	95 110 125 125 130 150 °C
Tempof Latex in Dip Tank (B)	25 -26 °C	29 -30
Oven Temp Before Coagulant Dip (C)	75 -80	90 -95
Calcium Nitrate (D)	7.0 - 8.0	11 - 12.0
Humidity (E)	Low	High
Calcium Nitrate (F)	2.5 -3.5 %	4.5 -5.5 %
Oven Temp Before Latex Dip (G)	170 -180	190 -200
pH of Latex Compound (H)	10.1 -10.5	10.6 -10.9

DEFINITION

- **Quality characteristics (responses)**
  - **performance indicators that could be identified and measured**
- **Controllable factors**
  - **factors that can be controlled**
- **Uncontrollable factors**
  - **factors that cannot be controlled or are difficult to control**
- **Robust - not sensitive to slight changes**

EXPERIMENTAL OBJECTIVES

- determine factors most influential on response
- determine where to set influential factor so that response is near the desired target value
- determine where to set the influential factor so that variability in response is small
- determine where to set the influential factor so that uncontrollable factors are minimised

Std run	Actual run	A	B	C	E	D	F	G	H
1	12	-	-	-	-	-	-	-	-
2	6	+	-	-	+	-	+	+	-
3	1	-	+	-	+	-	+	-	+
4	15	+	+	-	-	-	-	+	+
5	3	-	-	+	+	-	-	+	+
6	11	+	-	+	-	-	+	-	+
7	10	-	+	+	-	-	+	+	-
8	13	+	+	+	+	-	-	-	-
9	16	-	-	-	-	+	+	+	+
10	2	+	-	-	+	+	-	-	+
11	8	-	+	-	+	+	-	+	-
12	14	+	+	-	-	+	+	-	-
13	7	-	-	+	+	+	+	-	-
14	5	+	-	+	-	+	-	+	-
15	4	-	+	+	-	+	-	-	+
16	9	+	+	+	+	+	+	+	+

std run	actual run	curing temp	latex temp	humidity	calcium nitrate	calcium carbonate
1	12	95 110 125	29-30	low	11-12	4.5-5.5
2	6	95 110 125	25-26	low	7-8	4.5-5.5
3	1	80 100 115	25-26	high	7-8	2.5-3.5
4	15	80 100 115	29-30	high	11-12	4.5-5.5
•	•	•	•	•	•	•
•	•	•	•	•	•	•
•	•	•	•	•	•	•
•	•	•	•	•	•	•
•15	4	95 110 125	25-26	low	11-12	2.5-3.5
•16	9			low	7-8	4.5-5.5

RESULTS

- Humidity influences the mean response of thickness and pinholes
- Thickness and weight have a significant correlation but vice-versa for pinholes and strength.
- Interactions between controllable factors and humidity suggest that the process can be made robust to changes.
- The speed of the stirrer in the coagulant tank has to be kept sufficiently low to keep the pinholes level low.
- Models developed from this study could be used to facilitate changing manufacturing parameters to cope with changing customers' specifications.

RESULT SUMMARY

Response	Average	Std Deviation	Interaction
Tensile Strength	A,G	A	BG
Pinholes	B,G	B	BE
Thickness	B,D	-	BE
Weight	B,D,F	D,H	DF

BENEFITS

- Enhances the understanding of the rubber glove manufacturing process and a better control of the process.
- The experimental results showed that at 7.0-8.0 % Of calcium nitrate, the glove thickness could still be achieved within spec.
- A saving of 4.2% Of calcium nitrate could be made without any initial cost & effort. Moreover calcium nitrate is one of the expensive input.
- Factors that have no influence on the outputs could be relaxed.
- Automation for measuring and topping coagulant could drastically reduce downtime.
- Alternatively, a reduction in man-power could alleviate the labour shortage problem.
- The commitment of everyone in the company ensures succesful implementation of a project.